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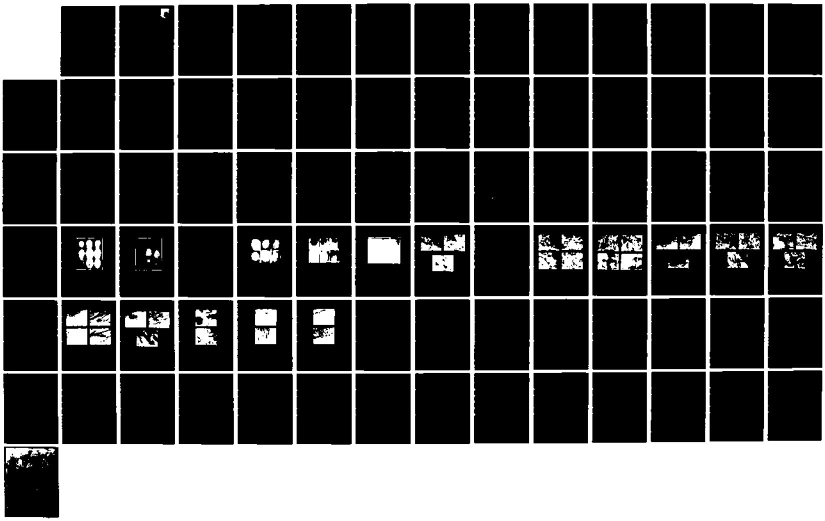

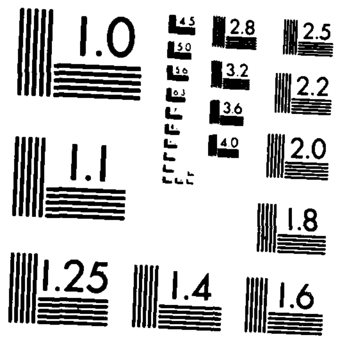

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SOLID PARTICLE EROSION PROCESSES IN THERMOSET AND THERMOPLASTIC COMPOSITE MATERIALS AND POLYURETHANE COATINGS

Joseph Zahavi
Israel Institute of Metals
Technion
Haifa, Israel

April 1983

Technical Report for period October 1981 - September 1982

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MATERIALS LABORATORY
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Solid particle erosion of polyurethane coatings of various composition and tensile modulus on E glass epoxy substrate and of uncoated composite materials of polyethylene terephthalate (PET) containing T-300 carbon fibers and E glass fibers have been investigated utilizing natural Mediterranean sea sand.

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Effects of impact angle (30^0 to 90^0) and sand weight impacted (200, 400 and 600 gr) have been investigated and materials behavior and response were characterized by weight loss, surface roughness and surface morphology and structure.

In all three types of polyurethane coatings on glass epoxy substrate, a progressive decrease of weight loss with the increase of the impact angle was observed. Maximum weight loss was obtained at an impact angle of 30 degrees indicating the ductile behavior of these coatings.

For the uncoated composite materials of polyethylene terephthalate, reinforced with T-300 carbon fibers or glass fibers, the weight loss increased with impact angle reaching a maximum at normal incident angle indicative of brittle behavior under erosive conditions despite the thermoplastic nature of the PET resin.

A progressive increase in target coatings weight loss with the amount of sand impacted was found in all types of polyurethane layers tested. Eroded coating surface roughness was found to follow target weight loss; the higher the weight loss the higher the value of surface roughness observed. Erosion processes in the coatings were associated with formation of microcracks, microcrack propagation and intersection resulting in fragments of coatings which were then locally removed from the surface.

For the uncoated composite materials tested, target weight loss increased with the increasing amount of sand impacted in the range of 200 gr to 600 gr. Polyethylene-terephthalate composite, reinforced with glass fibers, eroded about three times as much as the polyethylene-terephthalate containing T-300 carbon fibers. The erosion processes in the composite materials involved three main stages; (1) local removal of material in the resin areas, (2) erosion in the fibers associated with their breakage and (3) erosion of the interface zones between fibers and adjacent resin matrix.

PREFACE

This report summarizes research performed at the Israel Institute of Metals, Technion, Haifa, Israel from October 1981 to September 1982 under AFOSR Grant 81-0225. The work was initiated under Project 2422, "Protective Coatings and Materials, Task 242201, Coatings for Aircraft and Spacecraft" and was funded under P.E. 62102F.

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Thanks are due to the following: Mr. Shalom Feinberg for carrying out the experiments and Mr. Patrick Adamson of Universal Technology Corporation, Dayton, Ohio for preparation of the report and the figures therein.

TABLE OF CONTENTS

Page

1. Introduction 1

2. Experimental 1

2.1 Erosion Apparatus 1
2.2 Target Materials. 2
2.2.1 Glass Epoxy Composite. 2
2.3 Abrasive Sand Particles 6
2.4 Erosion Tests 6
2.5 Surface Characterization. 6
2.5.1 Microscopy 6
2.5.2 Roughness Measurement. 6

3. Results. 6

3.1 Erosion Kinetics. 7
3.1.1 Polyurethane Coated Glass Epoxy Composite. 7
3.1.1.1 Target Weight Change vs Impact Angle. 7
3.1.1.2 Target Weight Change vs Sand Weight Impacted. 12
3.1.2 Uncoated Polyethylene Terephthalate Reinforced Materials 12
3.1.2.1 Target Weight Change vs Impact Angle. 20
3.1.2.2 Target Weight Change vs Sand Weight Impacted. 20
3.2 Surface Roughness 24
3.2.1 Polyurethane Coatings on Glass Epoxy Composite 24
3.2.1.1 Polyurethane Coatings "A" 24
3.2.1.2 Polyurethane Coatings "B" 24
3.2.1.3 Polyurethane Coatings "C" 28
3.3 Microscopic Observations. 28
3.3.1 Optical Microscopy 28
3.3.1.1 Polyurethane Coatings on Glass Epoxy. 28
3.3.1.2 Uncoated Reinforced Polyethylene Terephthalate Composite 32
3.3.2 Scanning Electron Microscopy (S.E.M.). 32
3.3.2.1 Polyurethane Coatings on Glass Epoxy Composite 32
3.3.2.2 Uncoated Polyethylene Terephthalate Reinforced Composite. 37
3.3.2.2.1 Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers. 37
3.3.2.2.2 Polyethylene Terephthalate Reinforced with E Glass Cloth. . . . 43

4. Discussion 49

4.1 Polyurethane Coatings on Glass Epoxy Substrate 49
4.1.1 Effect of Angle and Sand Weight Impacted 49
4.1.2 Effects of Surface Roughness and Morphology. 50
4.1.3 Effect of Polyurethane Coatings Type 51

4.2 Composite Materials of Polyethylene Terephthalate Reinforced with (A) T-300 Carbon Fibers and (B) E Glass Cloth 51
4.2.1 Effects of Impingement Angle and Sand Weight Impacted 51
4.2.2 Effects of Surface Morphology and Structure 52

5. Conclusions 53

5.1 Polyurethane Coatings. 53
5.1.1 Erosion - Conclusions 53
5.1.2 Target Coating Weight Loss - Conclusions. 53
5.1.3 Surface Roughness - Conclusions 53
5.1.4 Erosion Processes - Conclusions 53
5.1.5 Ratios of NCO/OH and Tensile Modulus - Conclusions. . 53
5.2 Composite Materials. 54
5.2.1 Target Weight Loss - Conclusions. 54
5.2.2 Target Weight Loss in Direct Relationship w/Sand. . . 54
5.2.3 Basic Erosion Processes - Conclusions 54
5.2.4 Polyethylene Terephthalate Containing E Glass Fibers Erosion - Conclusions 54

References. 55

Appendix

A. Erosion Data of Coated and Noncoated Composite Materials . . 59
B. Surface Roughness Data 71

LIST OF ILLUSTRATIONS

Figure		Page
2.1	Sand Particle Impact Velocity as Function of Air Velocity at the Erosion Rig Apparatus for Air Velocities up to 180 [m/sec]	3
2.2	Sand Particle Impact Velocity as Function of Air Velocity at the Erosion Rig Apparatus for Air Velocities Above 180 [m/sec] up to 320 [m/sec]	4
3.1	Weight Change of Polyurethane of Type "A" on E Glass Epoxy as a Function of Impact Angle at 42 [m/sec]	8
3.2	Weight Change of Polyurethane of Type "A" on E Glass Epoxy as a Function of Impact Angle at 74.5 [m/sec]	9
3.3	Weight Change of Polyurethane Coating of Type "B" on E Glass Epoxy as a Function of Impact Angle at 42 [m/sec]	10
3.4	Weight Change of Polyurethane Coating of Type "C" on E Glass Epoxy as a Function of Impact Angle at 42 [m/sec]	11
3.5	Weight Change of Polyurethane Coating of Type "AB" on E Glass Epoxy as a Function of Impact Angle at 42 [m/sec]	13
3.6	Weight Change of Polyurethane Coating of Type "AC" on E Glass Epoxy as a Function of Impact Angle at 42 [m/sec]	14
3.7	Weight Change of Polyurethane Coating of Type "A" on E Glass Epoxy as a Function of Sand Weight Impacted at 42 [m/sec]	15
3.8	Weight Change of Polyurethane Coating of Type "B" on E Glass Epoxy as a Function of Sand Weight Impacted at 42 [m/sec]	16
3.9	Weight Change of Polyurethane Coating of Type "C" on E Glass Epoxy as a Function of Sand Weight Impacted at 42 [m/sec]	17
3.10	Weight Change of Polyurethane Coating of Type "AB" on E Glass Epoxy as a Function of Sand Weight Impacted at 42 [m/sec]	18
3.11	Weight Change of Polyurethane Coating of Type "AC" on E Glass Epoxy as a Function of Sand Weight Impacted at 42 [m/sec]	19
3.12	Weight Loss as a Function of Impact Angle for Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers at Impact Velocity of 42 [m/sec] and 74.5 [m/sec]	21
3.13	Weight Loss as a Function of Impact Angle for Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers and with E Glass Cloth Fibers at Impact Velocity of 42 [m/sec]	22

Figure		Page
3.14	Weight Loss as a Function of Sand Weight Impacted for Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers at Impact Velocity of 42 [m/sec] and 74.5 [m/sec] . .	23
3.15	Surface Roughness of Polyurethane Coating of Type "A" as a Function of Impact Angle of Eroding Sand at 42 [m/sec] . .	25
3.16	Surface Roughness of Polyurethane Coating of Type "A" as a Function of Impact Angle of Eroding Sand at 74.5 [m/sec] . .	26
3.17	Surface Roughness of Polyurethane Coating of Type "B" as a Function of Impact Angle of Eroding Sand at 42 [m/sec] . . .	27
3.18	Surface Roughness of Polyurethane Coating of Type "C" as a Function of Impact Angle of Eroding Sand at 42 [m/sec] . . .	29
3.19	Eroded Surface of Polyurethane Coatings Types "A", "B" and "C" Exposed to 200 gr, 400 gr and 600 gr Amounts of Sand Impacted at Impingement Angle of 90 Degrees and Impact Velocity of 42 m/sec Optical Micrographs	30
3.20	Eroded Surface of Polyurethane Coatings Types "A", "B" and "C" Exposed to 200 gr of Impacted Sand at Impact Velocity of 42 m/sec and Impingement Angles of 30, 60 and 90 Degrees Optical Micrographs.	31
3.21	Eroded Surfaces of Composite Material of Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers After Being Exposed to Sand Amounts of 200 gr and 600 gr at Impingement Angles of 30, 60 and 90 Degrees at Constant Velocity of 42 m/sec	33
3.22	Eroded Surfaces of Composite Material of Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers After Being Exposed to Sand Amounts of 200 gr and 400 gr at Impingement Angles of 30, 60 and 90 Degrees at Constant Velocity at 74.5 m/sec	34
3.23	Eroded Surfaces of Composite Material of Polyethylene Terephthalate Reinforced with E Glass Cloth Fibers After Being Exposed to Sand Amounts of 200 gr and 600 gr at Impingement Angles of 30, 60 and 90 Degrees at Constant Velocity of 42 m/sec	35
3.24	S.E.M. Micrographs of Polyurethane Coating of Type "A" on E Glass Epoxy Substrate After Exposure to 200 gr of Sand Impacted at Impingement Angle of 30 Degrees. (A) General View x 90 (B) Enlargement of A, x 490 (C) Enlargement of B, x 2000	36

Figure		Page
3.25	S.E.M. Micrographs of Polyurethane Coating of Type "A" on E Glass Epoxy Substrate After Exposure to 600 gr of Sand Impacted at Impingement Angle of 90 Degrees. (A) General View x 100. (B) Eroded Resin and Fibers x 520. (C) High Magnification of Eroded Fibers x 2000. (D) High Magnification of Eroded Resin Zone x 2100	38
3.26	S.E.M. Micrographs of Polyurethane Coating of Type "B" on E Glass Epoxy Substrate After Exposure to 200 gr of Sand Impacted at Impingement Angle of 30 Degrees. (A) General View x 540. (B) Enlargement of A x 2100. (C) High Magnification of Eroded Area Showing the Embedment of Sand Particles x 2000. (D) Very High Magnification of Eroded Area x 20,000	39
3.27	S.E.M. Micrographs of Polyurethane Coating of Type "C" on E Glass Epoxy Substrate After Exposure to 600 gr of Sand Impacted at Impingement Angle of 90 Degrees. (A) General View of the Eroded Coating x 300. (B) Enlargement of Area A Showing Embedment of Sand Particles as Well as Initial Formation of Microcracks x 1000. (C) High Magnification of Other Zone Showing the Initiation and Propagation of Microcracks x 1000	40
3.28	S.E.M. Micrographs of Polyethylene Terephthalate Containing T-300 Carbon Fibers (Specimen "D") After 600 gr Sand Impacted at 30 Degrees at 42 m/sec. (A) General Appearance of Eroded Area x 200. (B) Eroded Area Showing Breakage of Fibers x 1000. (C) High Magnification of Other Eroded Area x 1000	41
3.29	S.E.M. Micrographs of Polyethylene Terephthalate Containing T-300 Carbon Fibers (Specimen "D") After 600 gr Sand Impacted at 90 Degrees at 42 m/sec. (A) General View of the Eroded Area x 50. (B) High Magnification View of Eroded Area x 500. (C) Higher Magnification of Eroded Area Showing Fiber Breakage and Removal of Resin Material x 2000	42
3.30	S.E.M. Micrographs of Polyethylene Terephthalate Containing T-300 Carbon Fibers (Specimen "D") After 200 gr Sand Impacted at 90 Degrees at 74.5 m/sec. (A) General View of the Eroded Area x 50. (B) High Magnification View of Eroded Area x 500. (C) Higher Magnification of Eroded Area Showing Fiber Breakage and Removal of Resin Material x 2000	44
3.31	S.E.M. Micrographs of Polyethylene Terephthalate Containing T-300 Carbon Fibers (Specimen "D") After 200 gr Sand Impacted at 60 Degrees at 74.5 m/sec. (A) General View of the Eroded Area x 20. (B) Eroded Area with Broken Fibers x 500. (C) High Magnification of Eroded Area Showing Fibers and Broken Fibers x 1200	45

Figure		Page
3.32	S.E.M. Micrographs of Polyethylene Terephthalate Containing E Glass Fibers (Specimen "E") After 600 gr Sand Impacted at 30 Degrees at 42 m/sec. (A) General View of Eroded Area x 100. (B) High Magnification of Eroded Area Showing Broken Fibers x 500	46
3.33	S.E.M. Micrographs of Polyethylene Terephthalate Containing E Glass Fibers (Specimen "E") After 200 gr Sand Impacted at 300 Degrees at 42 m/sec. (A) General View of the Eroded Area x 30. (B) High Magnification of Eroded Area Showing Broken Fibers x 600	47
3.34	S.E.M. Micrographs of Polyethylene Terephthalate Containir E Glass Fibers (Specimen "E") After 200 gr Sand Impacted a 90 Degrees at 42 m/sec. (A) General View of Eroded Area x 20. (B) High Magnification of Eroded Area Showing Broke Fibers x 600	48

LIST OF TABLES

Table		Page
A.1	Weight Loss Data for Polyurethane Coating Type "A". Impact Velocity 42 m/sec.	59
A.2	Weight Loss Data for Polyurethane Coating Type "A". Impact Velocity 74.5 m/sec.	60
A.3	Weight Loss Data for Polyurethane Coating Type "B"	61
A.4	Weight Loss Data for Polyurethane Coating Type "C"	62
A.5	Weight Loss Data for Polyurethane Coating Type "AB"	63
A.6	Weight Loss Data for Polyurethane Coating Type "AC"	64
A.7	Weight Loss Data for Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers. Impact Velocity 42 m/sec.	65
A.8	Weight Loss Data for Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers. Impact Velocity 74.5 m/sec.	66
A.9	Weight Loss Data for Polyethylene Terephthalate Reinforced with E Glass Epoxy Fibers	67
B.1	Surface Roughness Data for Polyurethane Coating Type "A". Impact Velocity 42 m/sec.	71
B.2	Surface Roughness Data for Polyurethane Coating Type "A". Impact Velocity 74.5 m/sec.	72
B.3	Surface Roughness Data for Polyurethane Coating Type "B". Impact Velocity 42 m/sec.	73
B.4	Surface Roughness Data for Polyurethane Coating Type "C". Impact Velocity 42 m/sec.	74

1. INTRODUCTION

The sand erosion of composite materials and of polymeric coatings on composite materials has been a problem for various components of aircraft operating especially in sandy, dusty areas.

In recent previous work [1,2] the authors investigated sand erosion behavior of polymeric coatings such as polyurethane and fluorocarbon on composite substrates such as E-glass epoxy and quartz polyimide. The effects of sand impact, angle, weight of sand particles impacted together with surface measurements and electron microscopy examinations of the eroded surfaces were carried out [1,2]. The use of these coating materials significantly reduced the erosion damage on the composite materials.

The purpose of this study is to evaluate the sand erosion behavior of various polyurethane coatings on glass epoxy varying in their composition and tensile modules and also, composite materials of polyethylene Terephtholate containing various types of fibers such as T-300 carbon or glass cloth.

2. EXPERIMENTAL

2.1 Erosion Apparatus

Erosion studies have been carried out in an air-blast sand erosion rig. A detailed description of the system was reported previously[1,2]. The system operated with filtered compressed air at room temperature, which was partially by-passed through a sand reservoir from which the sand was picked up and introduced into the main stream through a control orifice. The air-sand stream then flowed through a 4:1 converging nozzle into the specimen chamber.

The air flow rate was measured with an orifice flow meter. The actual mean velocity of the sand entering the specimen chamber was measured by the time-of-flight device suggested by Ruff and Ives[3]. The device was inserted in place of the specimen chamber and calibrated against the normal air flow rate which was subsequently used for control. In the air velocity range used in this study (up to 320 m/sec), the sand velocity proved to be about one-third the air velocity, in agreement with the results of Ruff and Ives. The correlation between particle velocities (up to and above 50 m/sec) and air velocities are shown in Figs 2.1 and 2.2, respectively.

2.2 Target Materials. The test materials in this study were as follows:

2.2.1 Glass epoxy composite coated with different hardness white polyurethane coatings. The polyurethane coatings were prepared with the same polyol and pigment (TiO_2) compositions and reacted at 1.4/1 NCO/OH ratio, 1.7/1 NCO/OH ratio, and 2.1/1 NCO/OH ratio with a diisocyanate which, when cured, produced a soft, low tensile modulus (1.4/1) coating, a medium hardness, medium tensile modulus (1.7/1) coating and a hard, high tensile modulus (2.0/1) coating.

Physical properties of cured free films of each composition were found as follows:

Composition	NCO/OH	Tensile Modulus PSI (%) 100	200	300	Tensile Strength PSI	Elongation %
A	1.4/1	350	700	1800	3500	360
B	1.7/1	1000	2200	5700	6200	310
C	2/1	1400	2900	6600	--	300

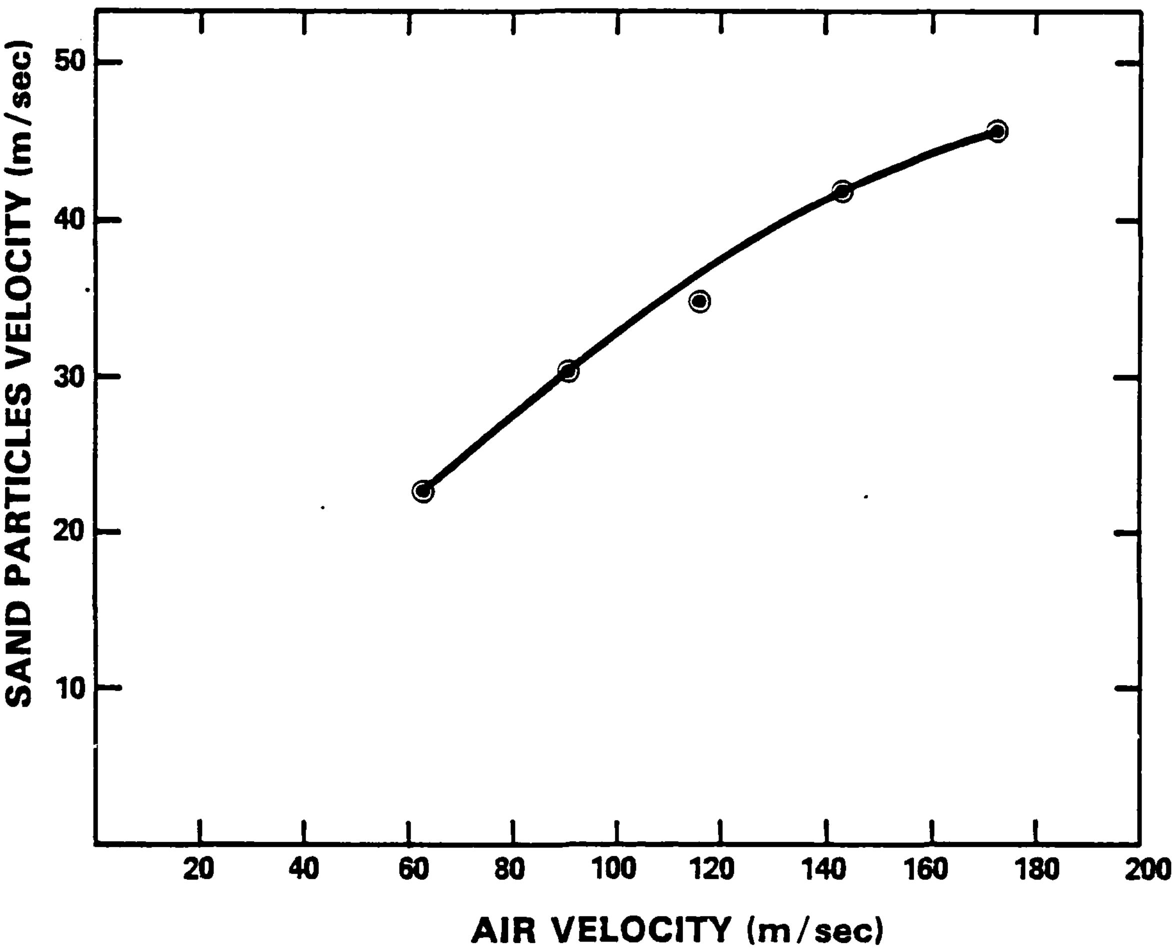


Fig. 2.1 Sand Particle Impact Velocity as Function of Air Velocity at the Erosion Rig Apparatus for Air Velocities up to 180 [m/sec].

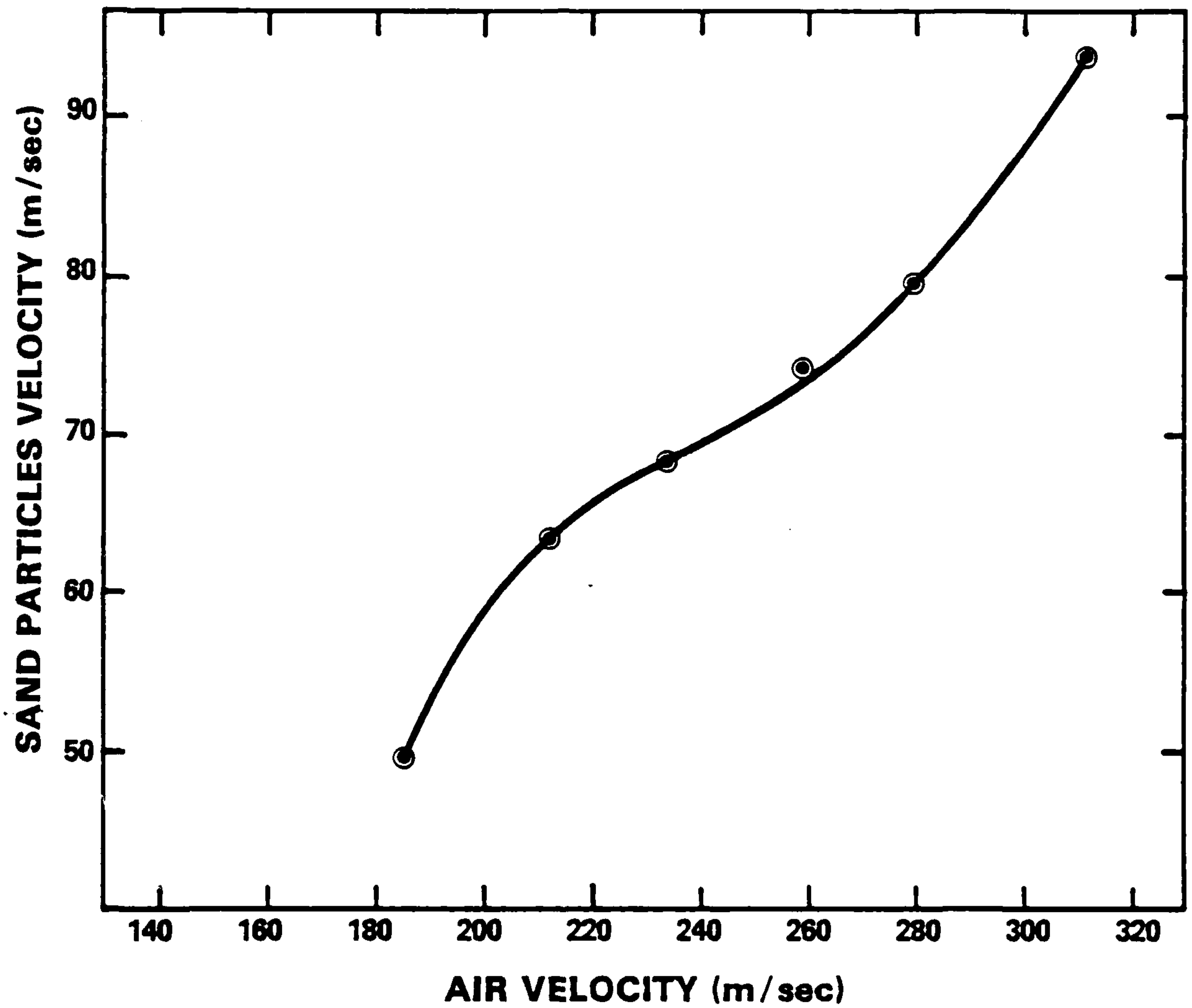


Fig. 2.2 Sand Particle Impact Velocity as Function of Air Velocity at the Erosion Rig Apparatus for Air Velocities Above 180 [m/sec] up to 320 [m/sec].

The various coatings and coating composition were applied to the glass epoxy specimens:

Specimen Designation	Coating	Thickness
"A"	Composition A [similar in properties to MIL-C-83445A]	12 mils
"B"	Composition B	12 mils
"C"	Composition C	12 mils
"AB"	8 mils Comp. A base + + 4 mils Comp. B topcoat	12 mils
"AC"	8 mils Comp. A base + + 4 mils Comp. C topcoat	12 mils

2.2.2 Uncoated materials. These specimen were:

Specimen Designation	Description
"D"	Polyethylene Terephthalate with T-300 carbon fiber reinforced
"E"	Polyethylene Terephthalate E-Glass cloth reinforcement

All the specimens were supplied by AFWAL/MLBE, Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433 U.S.A. Specimens of composite coated and uncoated materials were cut to measures of 50mm by 60mm.

2.3 Abrasive Sand Particles

Natural sand collected from the shore of the Mediteranean Sea was used in this study. The sand was sieved into the range of 210-297 μm and oven dried. The sand contained 96% by weight of SiO_2 which was considered to be responsible for its erosiveness[4]. Sand particles were slightly rounded and somewhat elongated.

2.4 Erosion Tests

The amounts of sand particles impacted on target materials varied from 200 gr to 600 gr at impact angles of 30°; 45°; 60°, 75° and 90°. Particle impact velocity used was 42.0 m/sec (at air velocity of 142.6 m/sec) and 74.5 m/sec (at air velocity of 259.2 m/sec). Before and after exposure the specimens were weighed to 0.1 mg on an analytical balance.

2.5 Surface Characterization

2.5.1 Microscopy. Optical and Scanning Electron Microscopy were used to characterize the morphology and structure of eroded specimen surfaces.

2.5.2 Roughness Measurement. A Talysurf (Hobson Model 3) was used to measure specimen surface roughness before and after being exposed to erosion conditions. Graphs of surface profile and surface roughness expressed as the centerline average (CLA) were obtained[1,2].

3. RESULTS

3.0 The materials investigated were classified into two major groups:

a. Glass epoxy composites coated with various white polyurethane coatings.

b. Polyethylene Terephthalate reinforced by T-300 carbon fibers and by E-Glass cloth.

The results obtained under various sand erosion conditions are described in the following sections.

3.1 Erosion Kinetics

3.1.1 Polyurethane Coated Glass Epoxy Composite. Erosion data, namely, targets weight change of glass epoxy composite coated with various types of polyurethane, obtained under various sand erosion conditions are summarized in Appendix A, Tables A.1 to A.6 and shown graphically in Figures 3.1 to 3.11.

3.1.1.1 Target Weight Change versus Impact Angle. The effects of sand particle impact angle on the mass change of the target under the impact of constant masses of sand and constant impact velocities are shown in Figures 3.1 to 3.6. Figures 3.1 and 3.2 show the behavior of polyurethane coating "A" on glass epoxy substrate under the impact of 200, 400 and 600 gr of abrasive sand particles at impact velocity of 42 m/sec and 74.5 m/sec, respectively. Maximum weight loss was found at an impact angle of 30°; whereas in the ranges of 35°-45° and 45°-60°, a zero weight loss was observed for target materials exposed to impact velocities of 42 m/sec and 74.5 m/sec, respectively (Figs 3.1, 3.2). Increasing the impact angle to 90° led to target weight gain for both velocities, as shown in Fig 3.1 and 3.2.

It should be noted that at an impact angle of 30°, under constant particle velocity of 74.5 m/sec, the maximum target weight losses were in the range of 5 to 25 mg (Fig 3.2) compared to 1 to 3 mg at constant velocity of 42 m/sec (Fig 3.1).

The behavior of polyurethane coatings "B" and "C" on glass epoxy substrate under erosion conditions is shown in Figs 3.3 and Fig 3.4, respectively. It was found that under constant amount of sand particles impacted (200, 400 and 600 gr) at constant velocity of 42 m/sec, a maximum weight loss was obtaind at a low incidence angle of 30°. Increase in

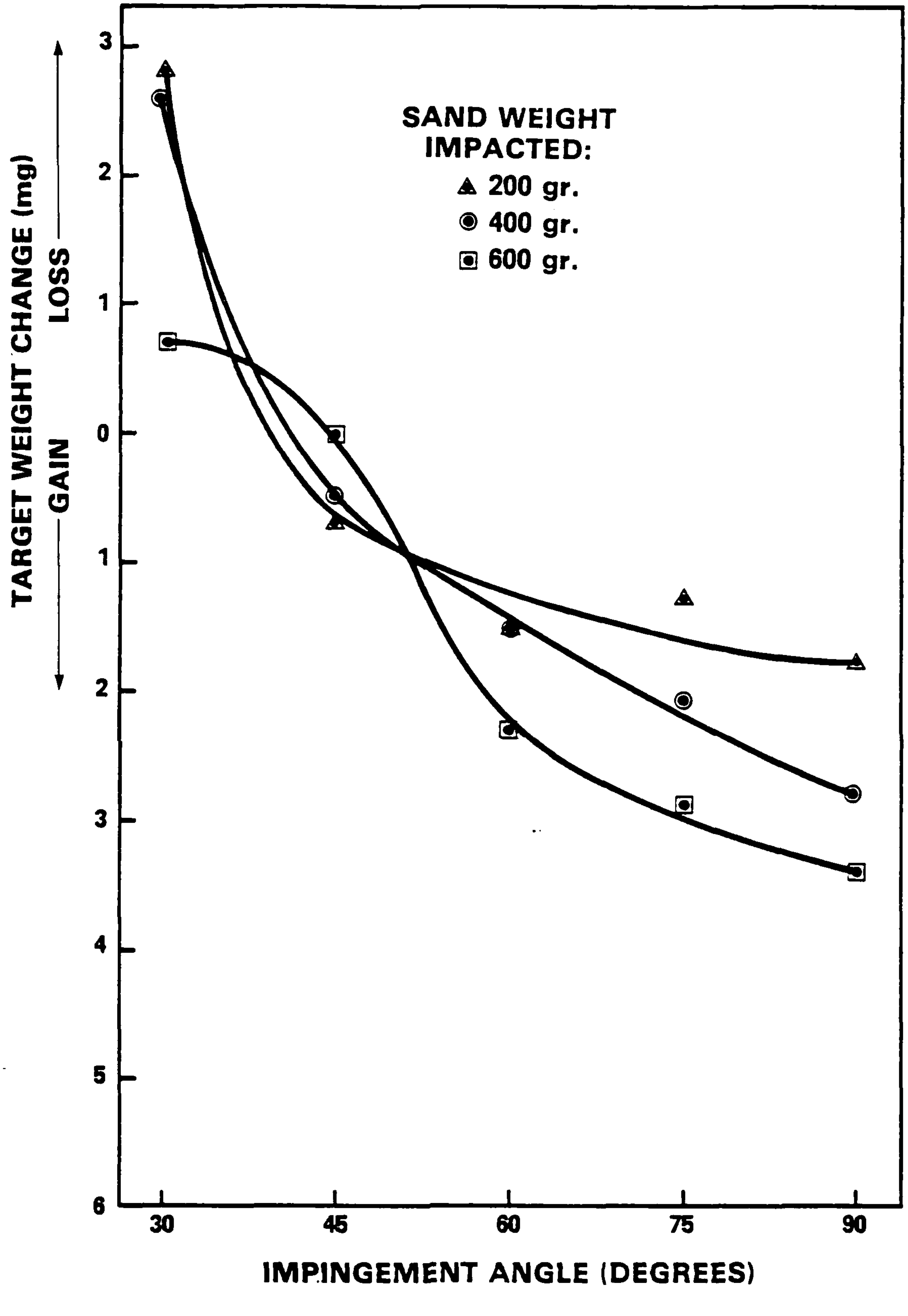


Fig. 3.1 Weight Change of Polyurethane of Type "A" on E Glass Epoxy as a Function of Impact Angle at 42 [m/sec].

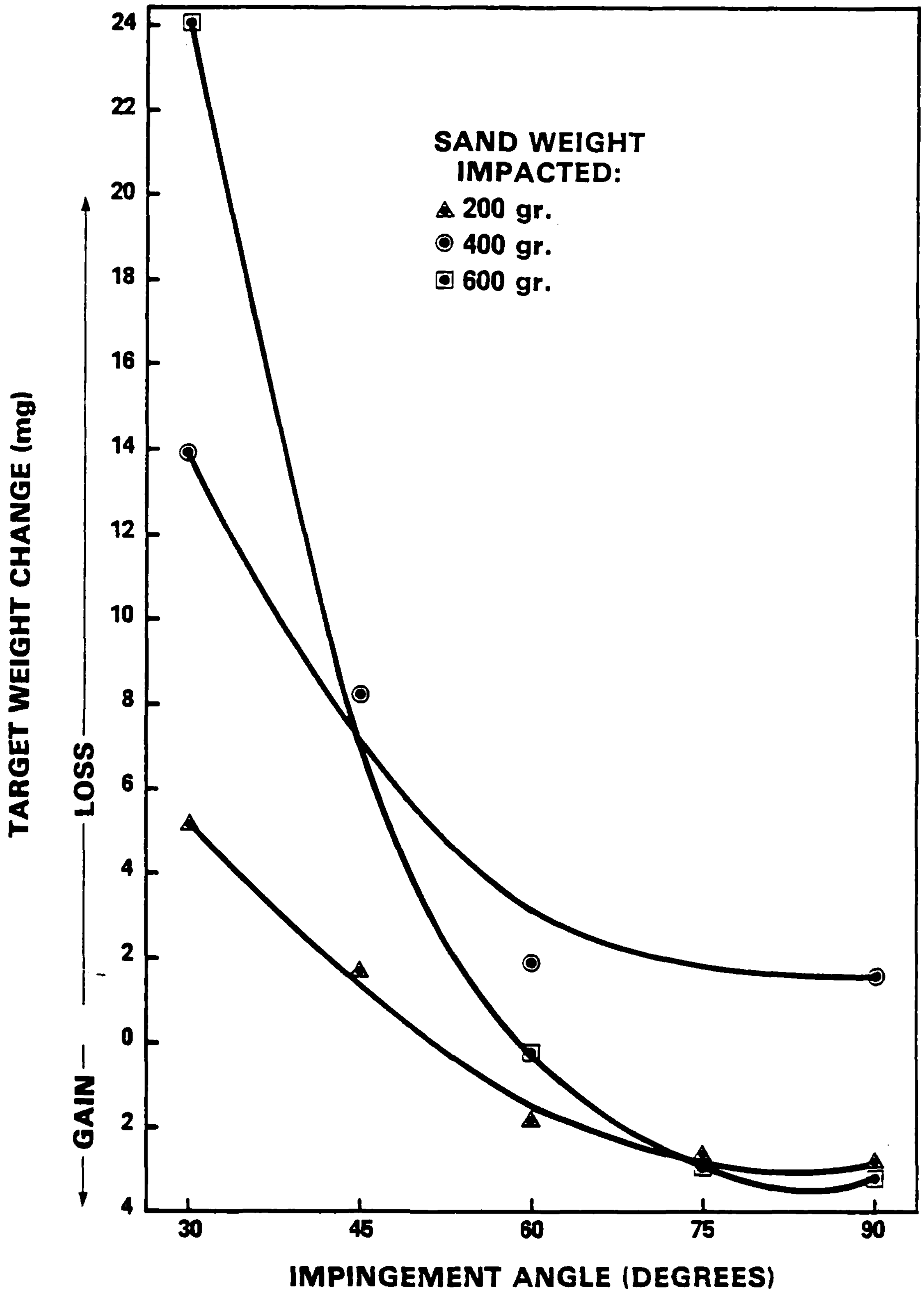


Fig. 3.2 Weight Change of Polyurethane of Type "A" on E Glass Epoxy as a Function of Impact Angle at 74.5 [m/sec].

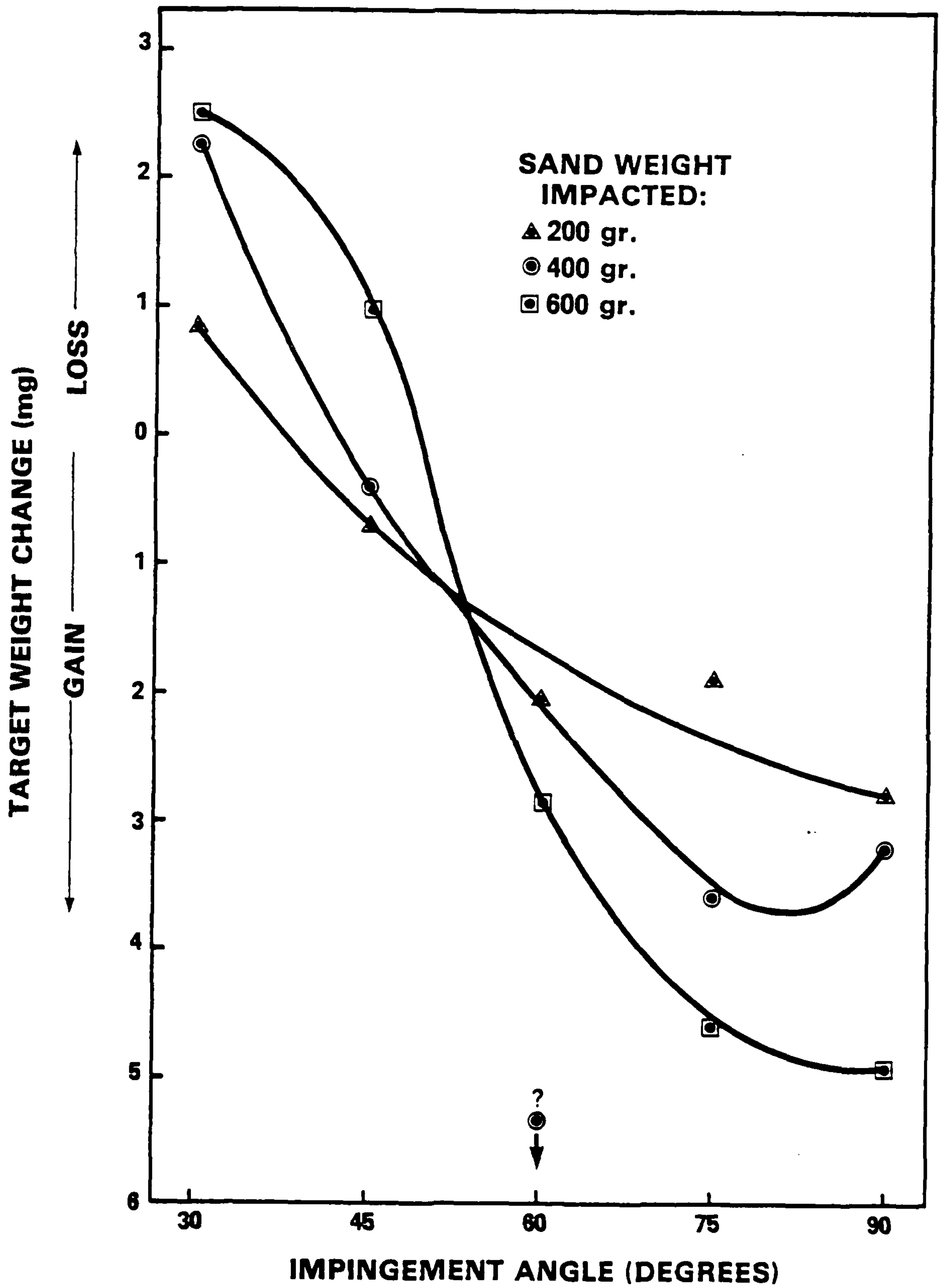


Fig. 3.3 Weight Change of Polyurethane Coating of Type "B" on E Glass Epoxy as a Function of Impact Angle at 42 [m/sec].

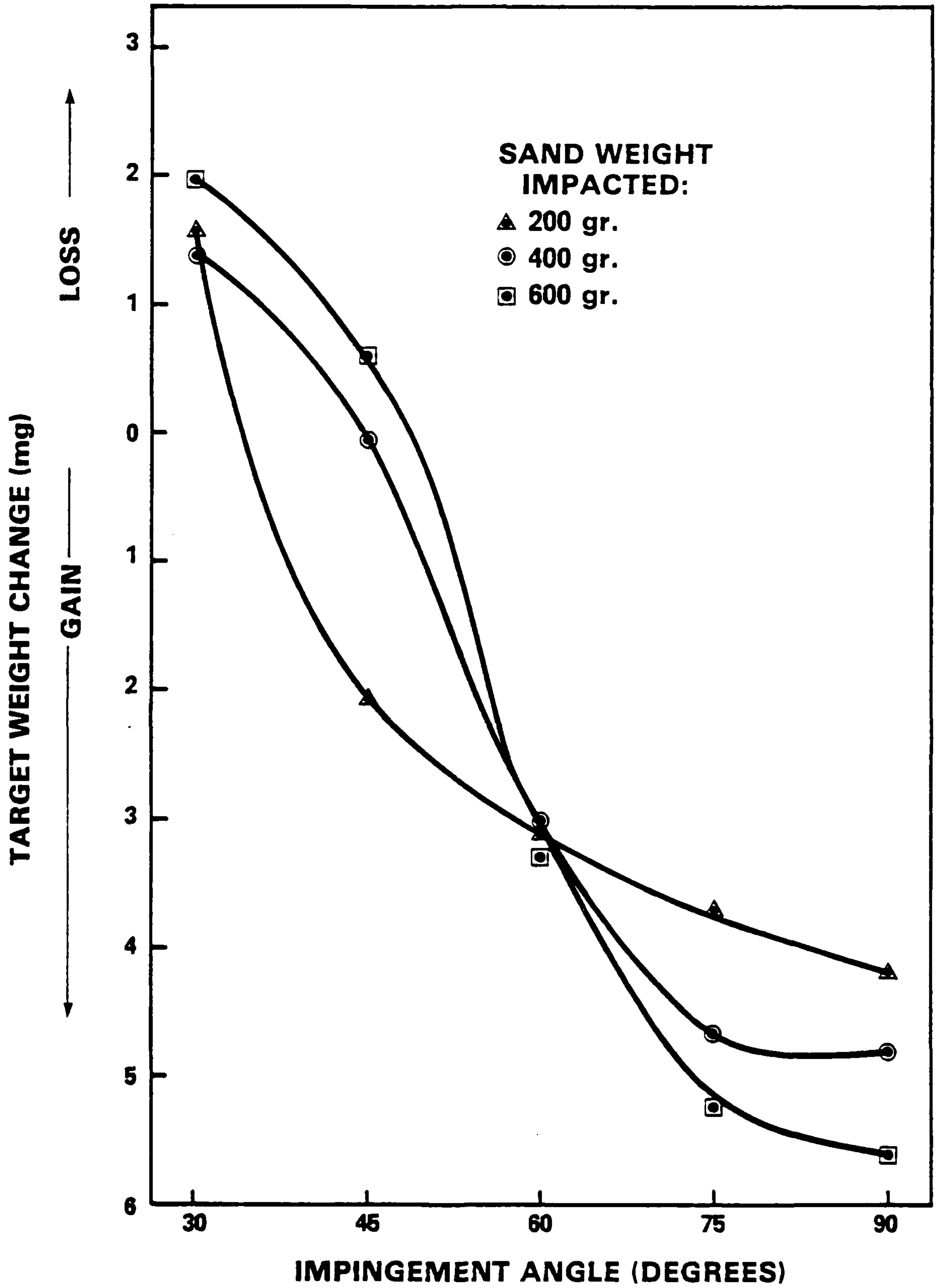


Fig. 3.4 Weight Change of Polyurethane Coating of Type "C" on E Glass Epoxy as a Function of Impact Angle at 42 [m/sec].

impact angle resulted in decrease of target weight loss up to a zero weight change at impact angles around 35° to 50° (Figs 3.3, 3.4). Further increase in impact angle up to 90° resulted in target weight gain. Target weight gain was in direct relationship to the amount of sand impacted, as shown in Figs 3.3 and 3.4.

The correlation found between target weight change of polyurethane coating "AB" and "AC" on glass epoxy and sand particle impingement angle are shown in Fig 3.5 and Fig 3.6 respectively. Weight change as function of impingement angle was obtained under constant amounts of 200, 400 and 600 gr of sand particles impacted at 42 m/sec. For both coatings, maximum target weight loss was found at an impact angle of 30°; whereas at approximately 40-50°, a zero weight loss was observed. Increasing the impact angle resulted in target weight gain as shown in Fig 3.5 and 3.6.

3.1.1.2 Target Weight Change Versus Sand Weight Impacted. A correlation between weight change of polyurethane coatings on glass epoxy substrate and the amount of sand particles impacted at constant impact angles is shown in Figs 3.7 to 3.11. Increasing the amount of sand weight impacted in the range of 200 to 600 gr resulted in an increase of target weight gain at constant impact angles of 60-90° for all the polyurethane coatings, as shown in Figs 3.7 to 3.11. However, at impact angles of 30 and 45°, and increase in the amount of sand impacted resulted in progressive target weight losses, as shown in Fig 3.7 for coating "A" (except at 30° and 600 gr sand), Fig 3.8 for coating "B", Fig 3.9 for coating "C", Fig 3.10 for coatings "AB" and Fig 3.11 for coatings "AC" (except at 45° and 600 gr sand). Although the polyurethane coatings differed in their properties, they behaved basically the same under identical erosion conditons and the amounts of target weight losses or gains were in the same range for all the coatings investigated.

3.1.2 Uncoated Polyethylene Terephthalate Reinforced Materials. Exposure of polyethylene terephthalat reinforced by T-300 carbon fiber

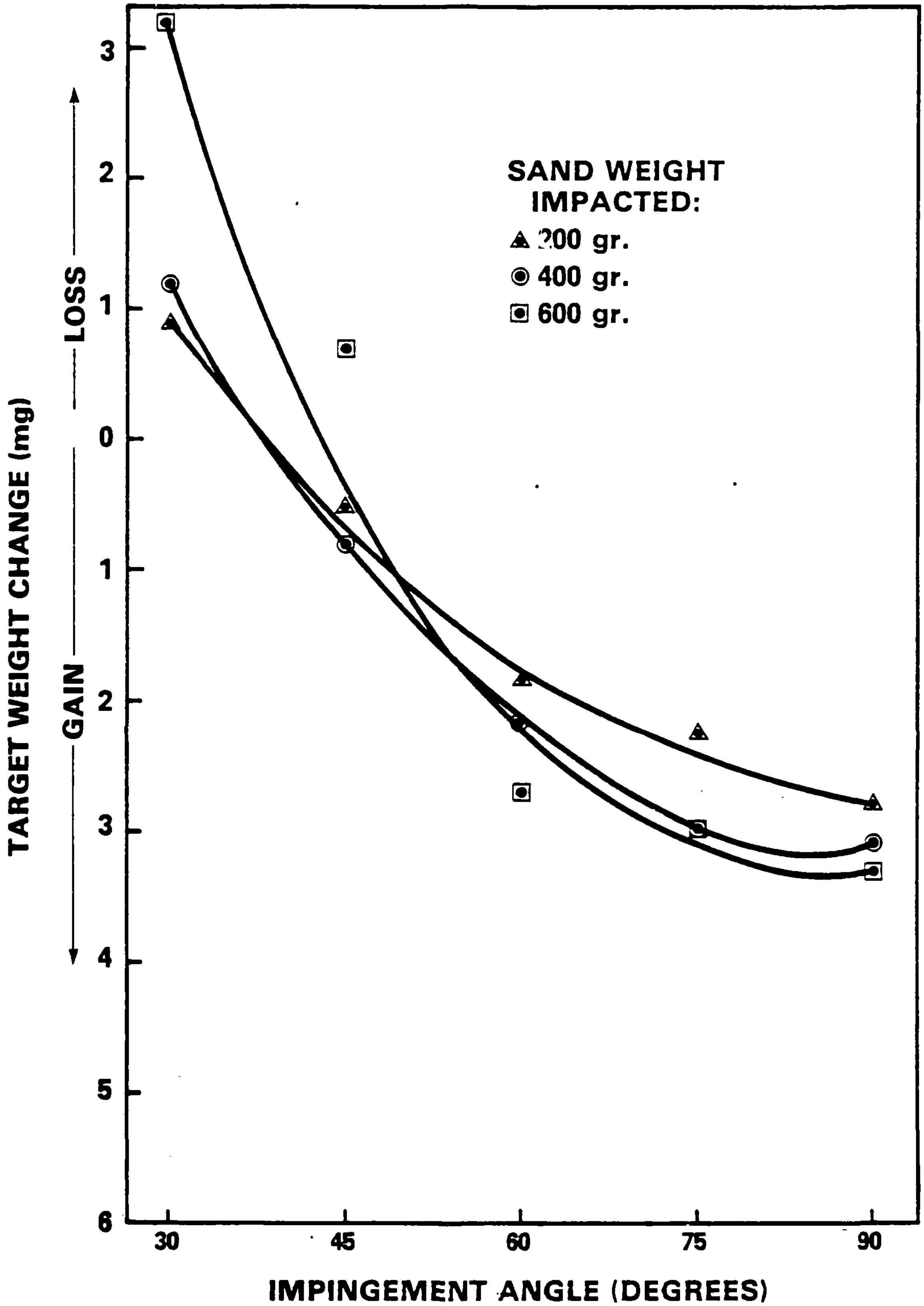


Fig. 3.5 Weight Change of Polyurethane Coating of Type "AB" on E Glass Epoxy as a Function of Impact Angle at 42 [m/sec].

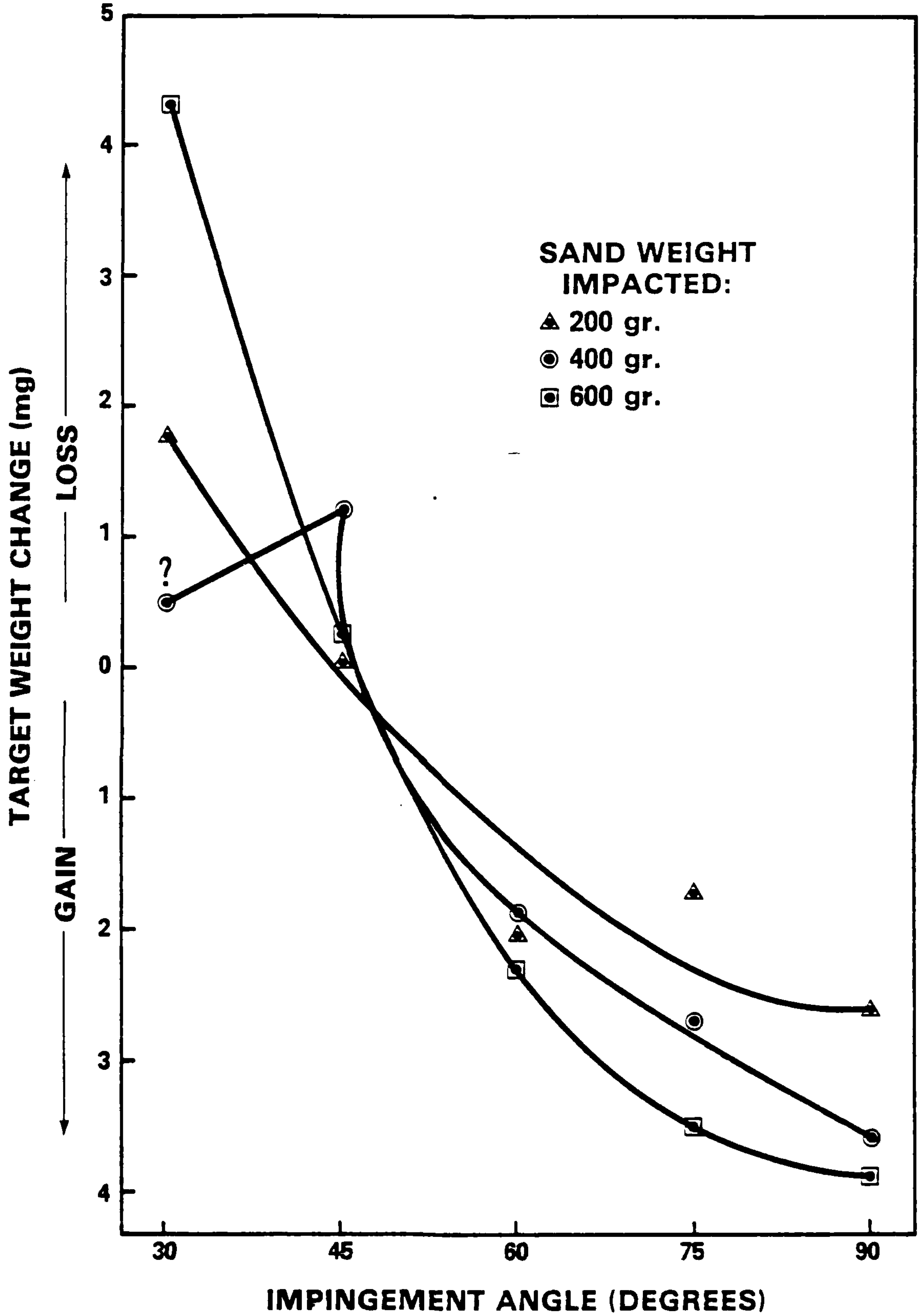


Fig. 3.6 Weight Change of Polyurethane Coating of Type "AC" on E Glass Epoxy as a Function of Impact Angle at 42 [m/sec].

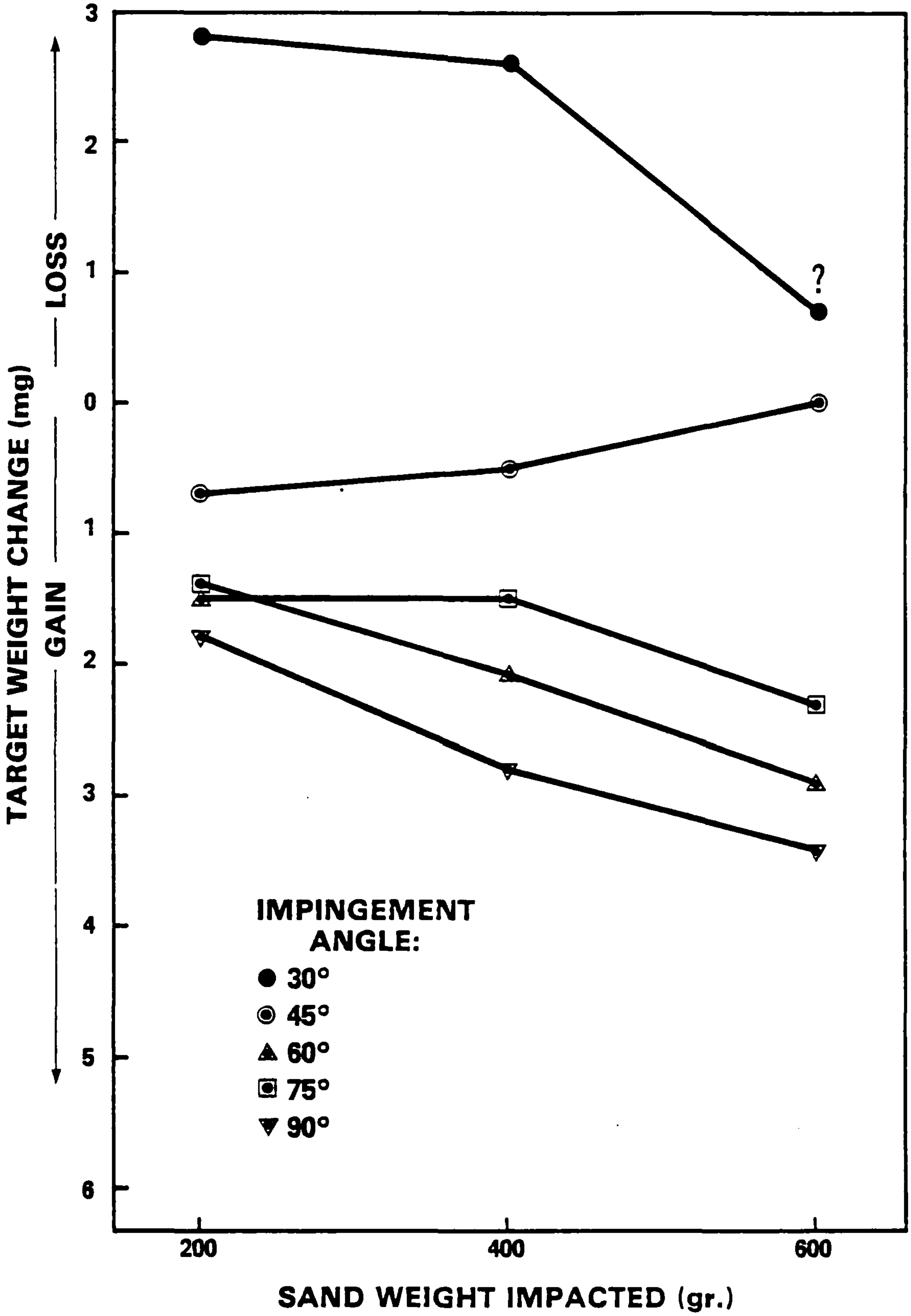


Fig. 3.7 Weight Change of Polyurethane Coating of Type "A" on E Glass Epoxy as a Function of Sand Weight Impacted at 42 [m/sec].

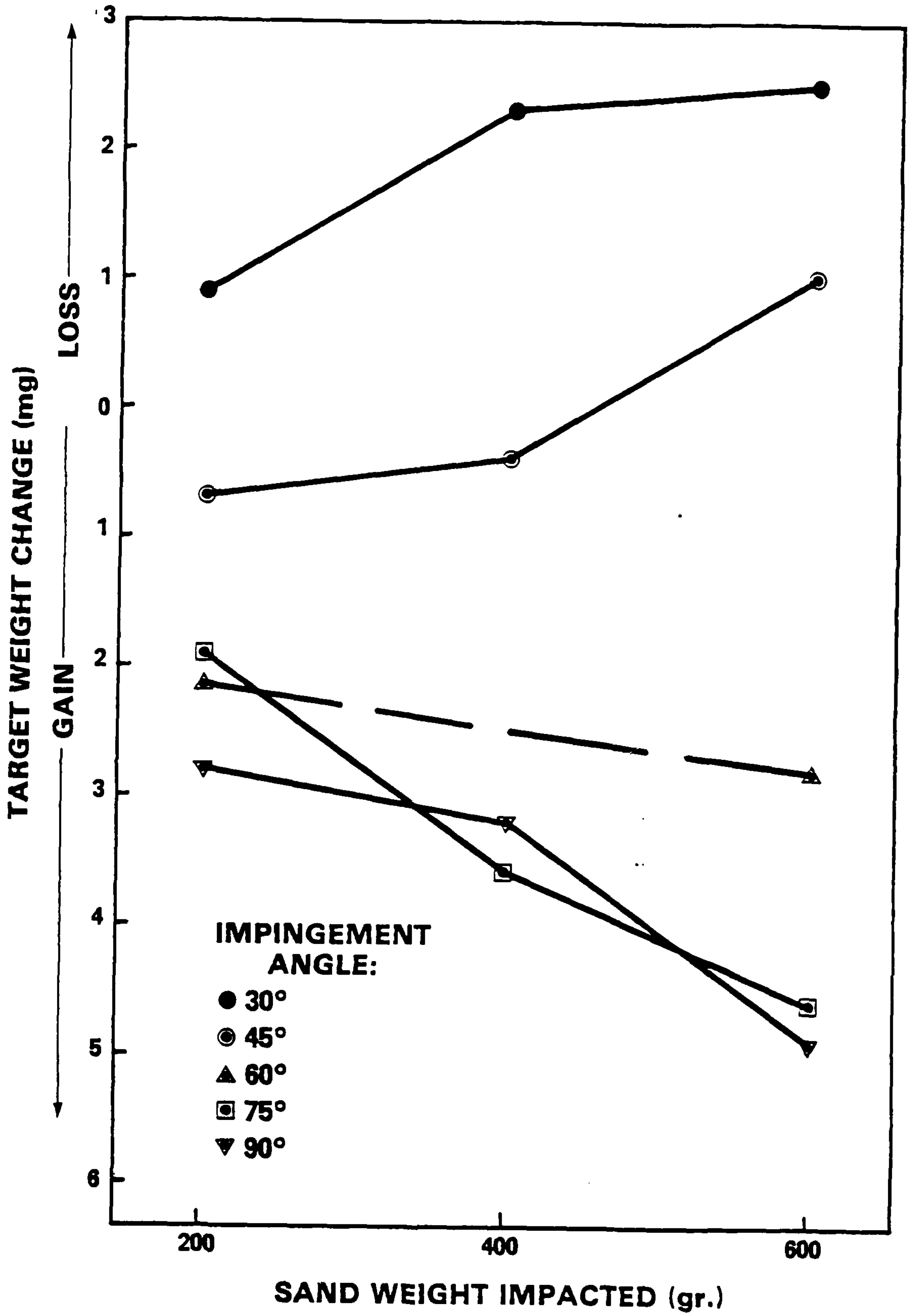


Fig. 3.8 Weight Change of Polyurethane Coating of Type "B" on E Glass Epoxy as a Function of Sand Weight Impacted at 42 [m/sec].

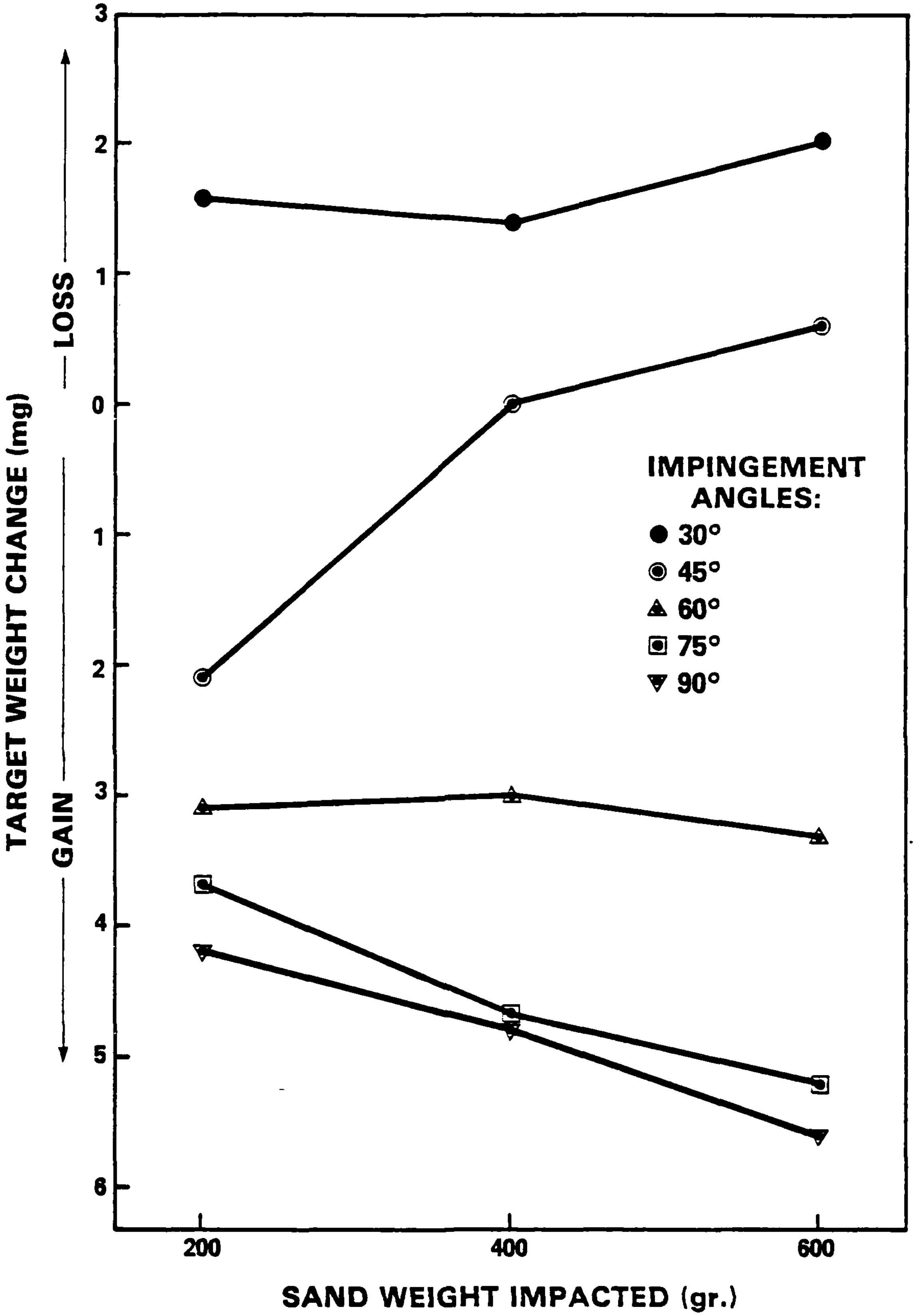


Fig. 3.9 Weight Change of Polyurethane Coating of Type "C" on E Glass Epoxy as a Function of Sand Weight Impacted at 42 [m/sec].

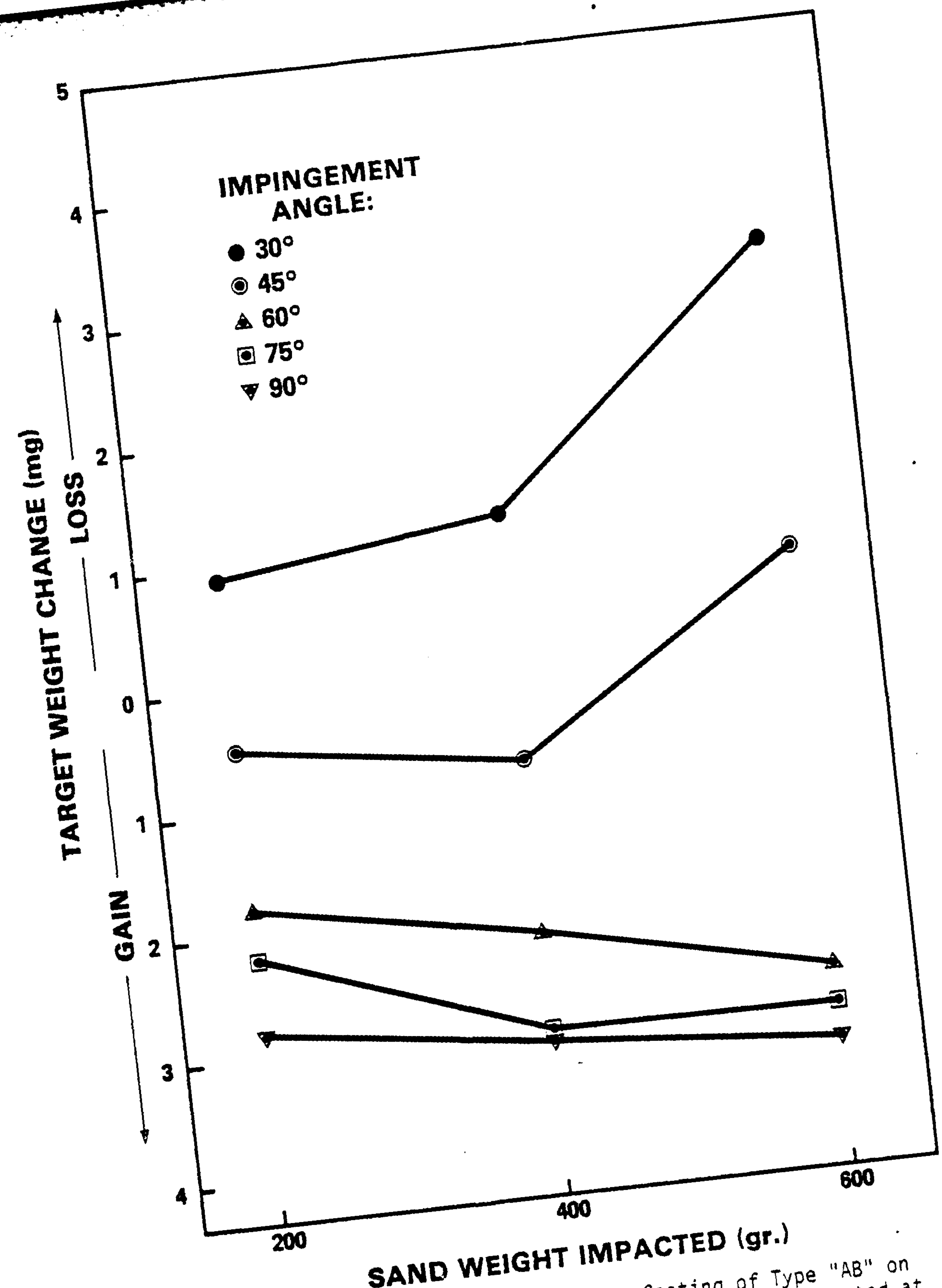


Fig. 3.10 Weight Change of Polyurethane Coating of Type "AB" on E Glass Epoxy as a Function of Sand Weight Impacted at 42 [m/sec].

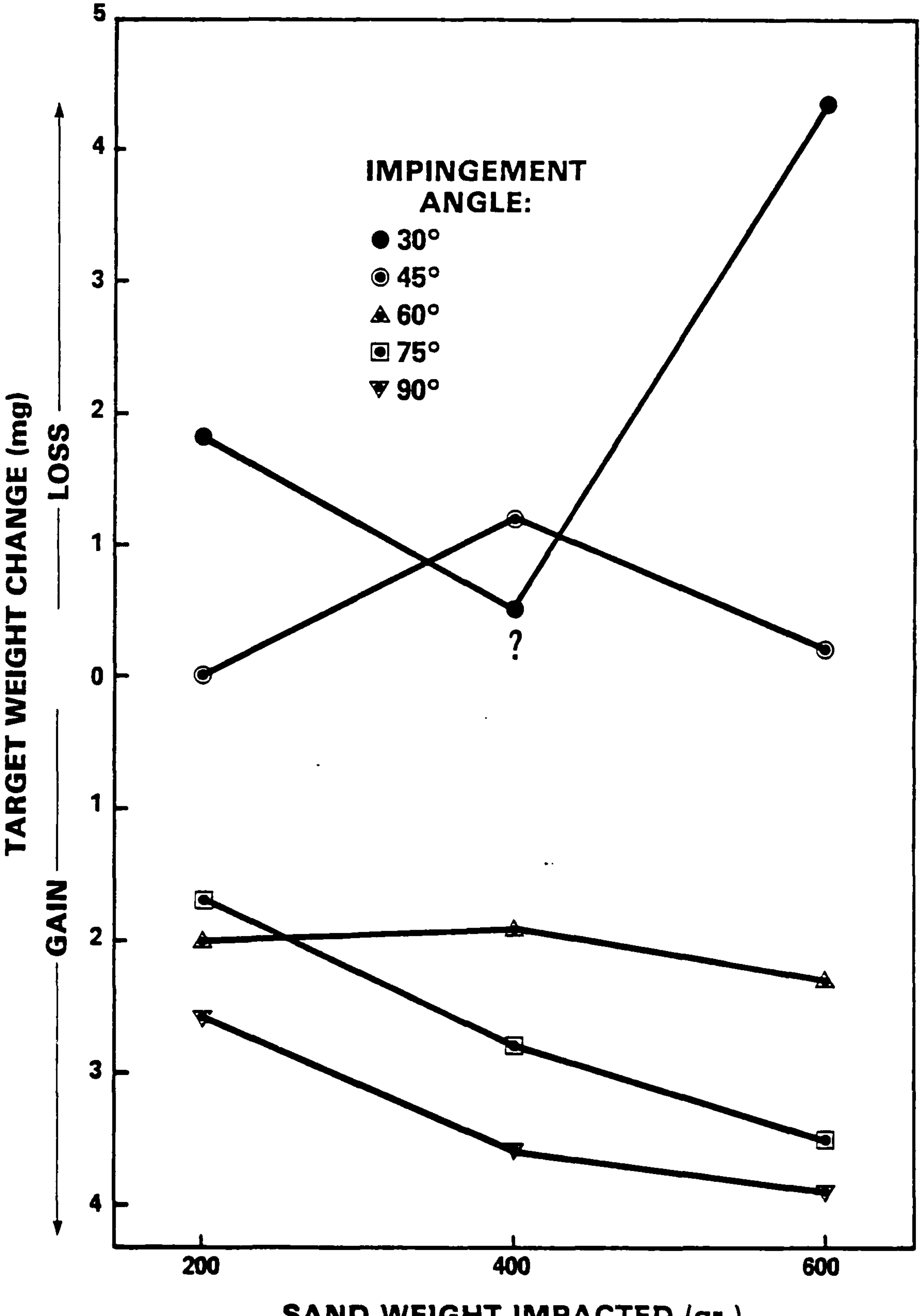


Fig. 3.11 Weight Change of Polyurethane Coating of Type "AC" on E Glass Epoxy as a Function of Sand Weight Impacted at 42 [m/sec].

(specimen "D") or E-Glass cloth (specimen "E") to various sand erosion conditions resulted in erosive damage to the material. The experimental data are summarized in Appendix A, Tables A.7, A.8 and A.9 and in Figures 3.12, 3.13 and 3.14.

3.1.2.1 Target Weight Change Versus Impact Angle. The dependence of the target weight loss on sand impingement angle is shown in Figs 3.12 and 3.13 for specimen "D" and "E", respectively. Figure 3.12 shows the behavior of polyethylene Terephthalate reinforced by T-300 carbon fibers under the impact of 200, 400 and 600 gr abrasive sand particles at constant impact velocities of 42 m/sec and 74.5 m/sec. A progressive increase in target weight loss was observed with an increase in the impact angle up to 90°, where a maximum weight loss was found for velocities of 42 m/sec and 74.5 m/sec, as shown in Fig 3.12. The amounts of target weight losses at 74.5 m/sec were about 5-6 times greater than the amounts observed at 42 m/sec under the same impact angle (Fig 3.12).

The dependence of target weight loss of polyethylene Terephthalate reinforced with E-Glass cloth (specimen "E") on impingement angles is shown graphically in Fig 3.13 where it is also compared to specimen"D". Target weight loss increased with impact angles reaching maximum values at 90° for impacted sand amounts of 400 and 600 gr for specimen "D" and "E" (Fig 3.13). The amount of target weight loss for specimen "E" was higher compared to specimen "D" under the same erosion condition. For example, at impact angle of 90° and 600 gr of sand impacted, target weight loss for specimen "E" was about 1800 mg compared to about 700 mg for specimen "D" under the same conditions (Fig 3.13).

3.1.2.2 Target Weight Change Versus Sand Weight Impacted. A correlation between weight loss of polyethylene Terephthalate reinforced with T-300 carbon fibers (specimen "D") and the amount of sand particles impacted at constant impact angles and velocities is shown in Fig 3.14. A progressive target weight loss was found with increase of sand impacted (200 gr to 600 gr) at velocity of 42 m/sec and 74.5 m/sec. The amount of

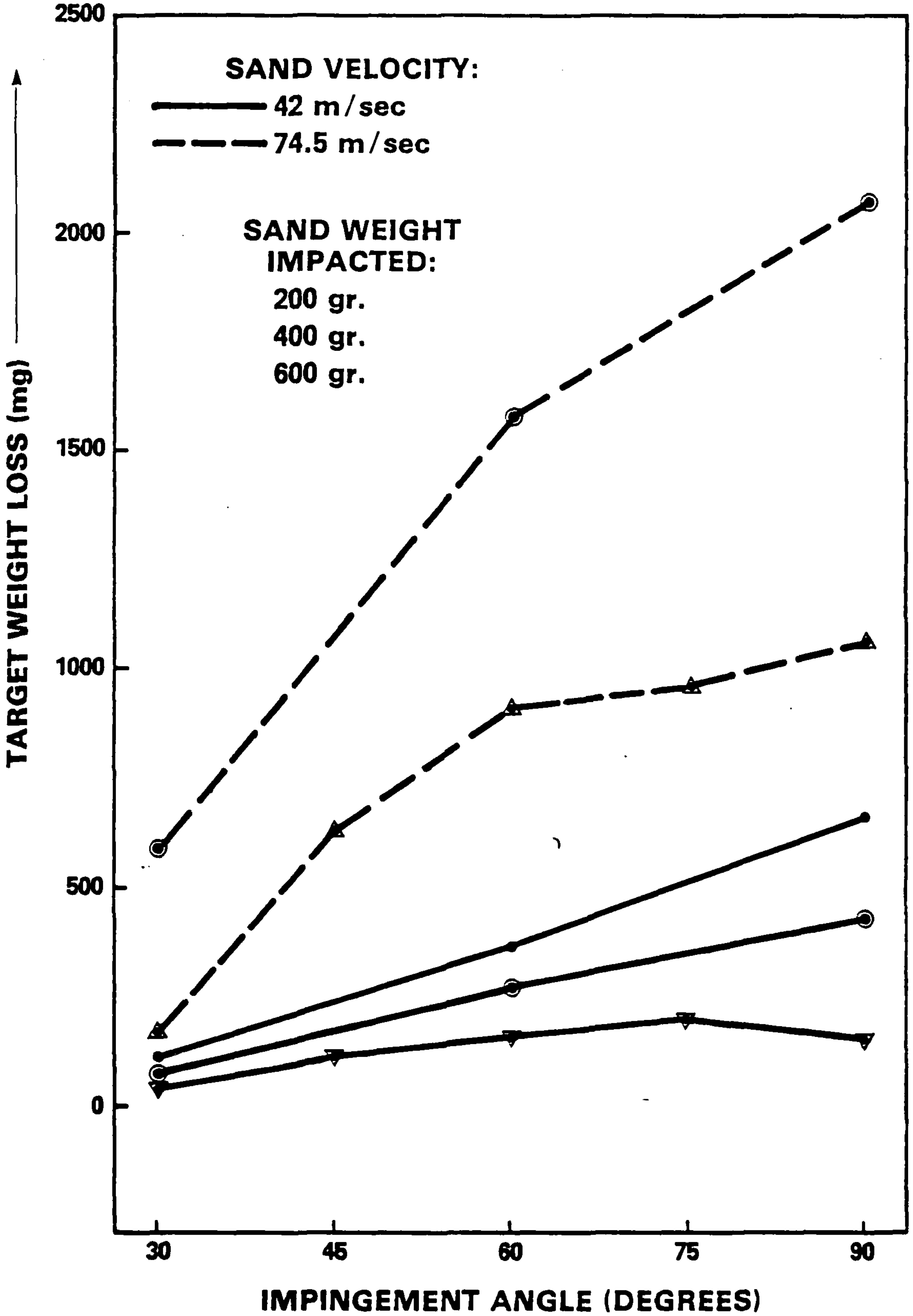


Fig. 3.12 Weight Loss as a Function of Impact Angle for Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers at Impact Velocity at 42 [m/sec] and 74.5 [m/sec].

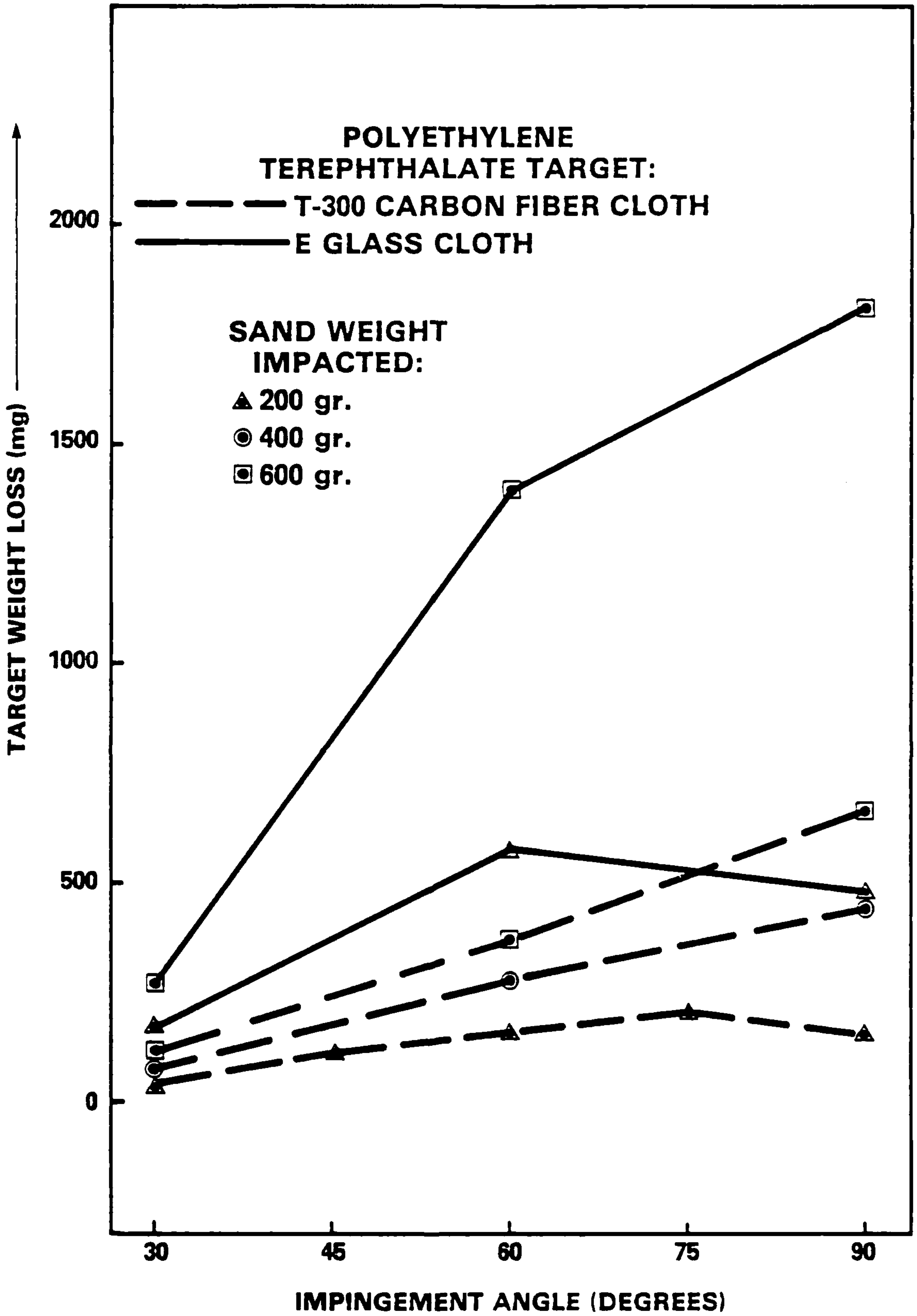


Fig. 3.13 Weight Loss as a Function of Impact Angle for Polyethylene Terephthlate Reinforced with T-300 Carbon Fibers and with E Glass Cloth Fibers at Impact Velocity of 42 [m/sec].

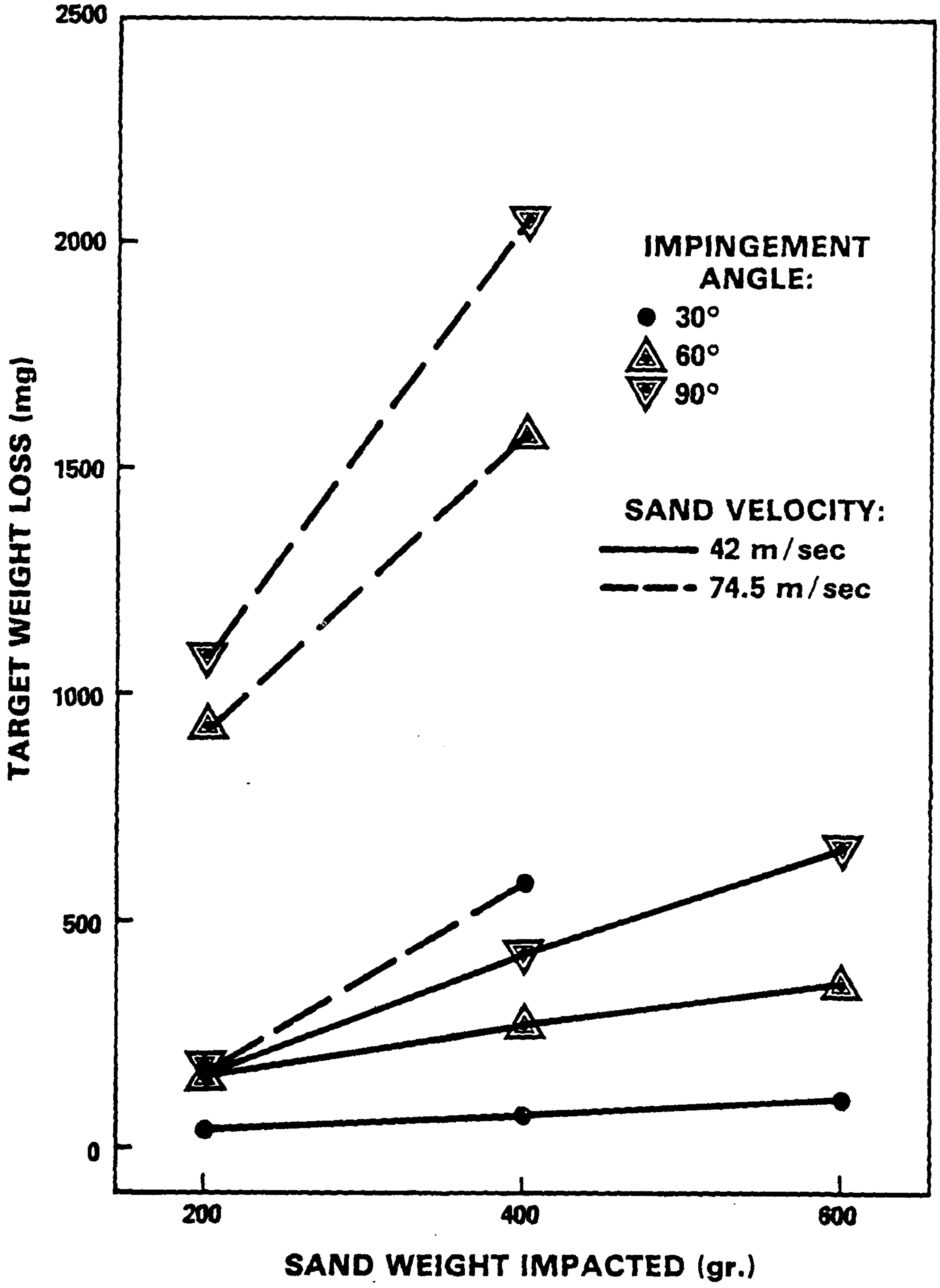


Fig. 3.14 Weight Loss as a Function of Sand Weight Impacted for Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers at Impact Velocity of 42 [m/sec] and 74.5 [m/sec]

target weight loss at impact velocity of 74.5 m/sec was about 5 times as much compared to the lower velocity of 42 m/sec under the same erosion conditions, as shown in Fig 3.14.

3.2 Surface Roughness

3.2.1 Polyurethane Coatings on Glass Epoxy Composite. The characterization of eroded coatings surface included measurements of surface roughness. The data obtained are summarized in Appendix B, Tables B.1 to B.4, and are shown graphically in Figs 3.15 to 3.18 for coatings "A", "B" and "C".

3.2.1.1 Polyurethane Coatings "A". The changes of coatings surface roughness with impact angle at various amounts of sand impacted and at impact velocity of 42 m/sec and 74.5 m/sec, are shown in Figs 3.15 and 3.16, respectively. A progressive decrease of surface roughness from maximum values (in the range of 0.6-1.0 micron) at impact angle of 30° to low values (around 0.5) at 90° for constant impact velocity of 42 m/sec, as shown in Fig 3.15.

At impact velocity of 74.5 m/sec high surface roughness C.L.A. around 1.0-2.5 microns was obtained at impingement angle of 45° for all amounts of sand impacted. Low surface roughness C.L.A. around 0.5 micron was obtained at normal impact angle as shown in Fig 3.16.

3.2.1.2 Polyurethane Coatings "B". The correlation found between coating surface roughness, expressed in Center Line Average (C.L.A) [μm], and sand impact angles for constant amounts of 200 gr, 400 gr and 600 gr at constant impact velocity of 42 m/sec is shown in Fig 3.17. Maximum surface roughness (in the range of 0.7 to 1.3) was obtained at impact angle of 45° for all amounts of sand impacted. A decrease in surface roughness was found with increasing impact angle reaching values around 0.5 micron at normal impact angle (Fig 3.17).

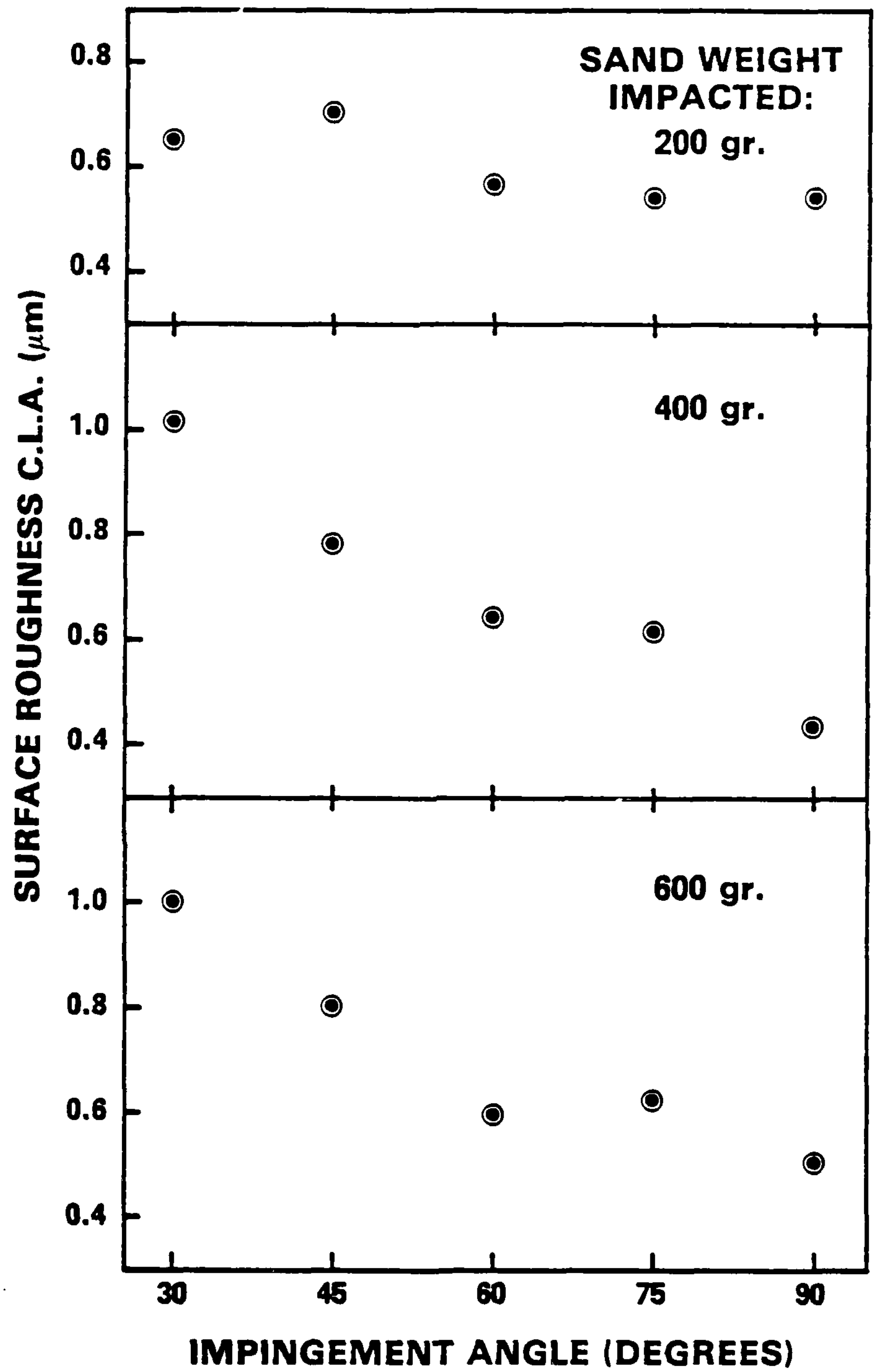


Fig. 3.15 Surface Roughness of Polyurethane Coating of Type "A" as a Function of Impact Angle of Eroding Sand at 42 [m/sec].

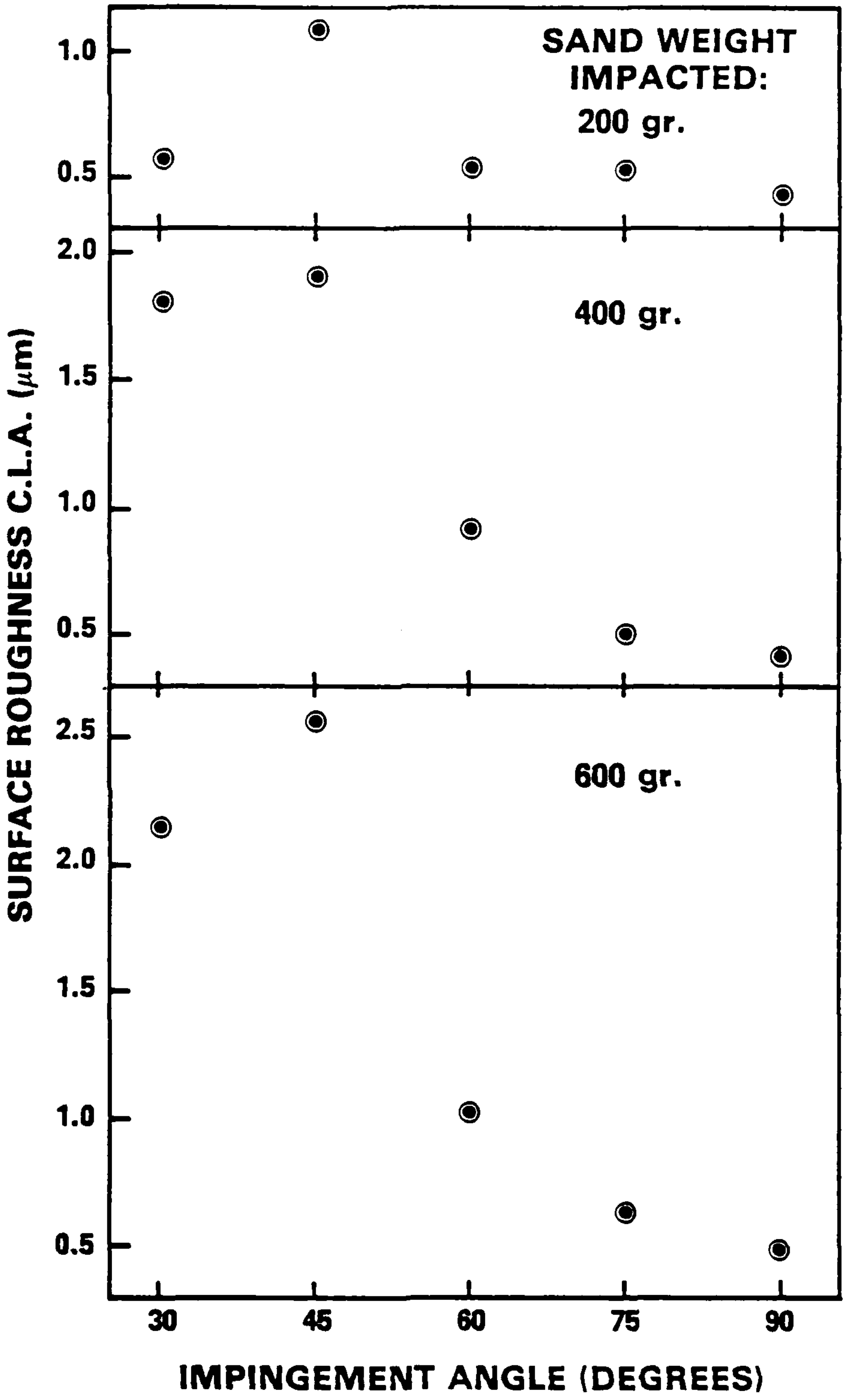


Fig. 3.16 Surface Roughness of Polyurethane Coating of Type "A" as a Function of Impact Angle of Eroding Sand at 74.5 [m/sec].

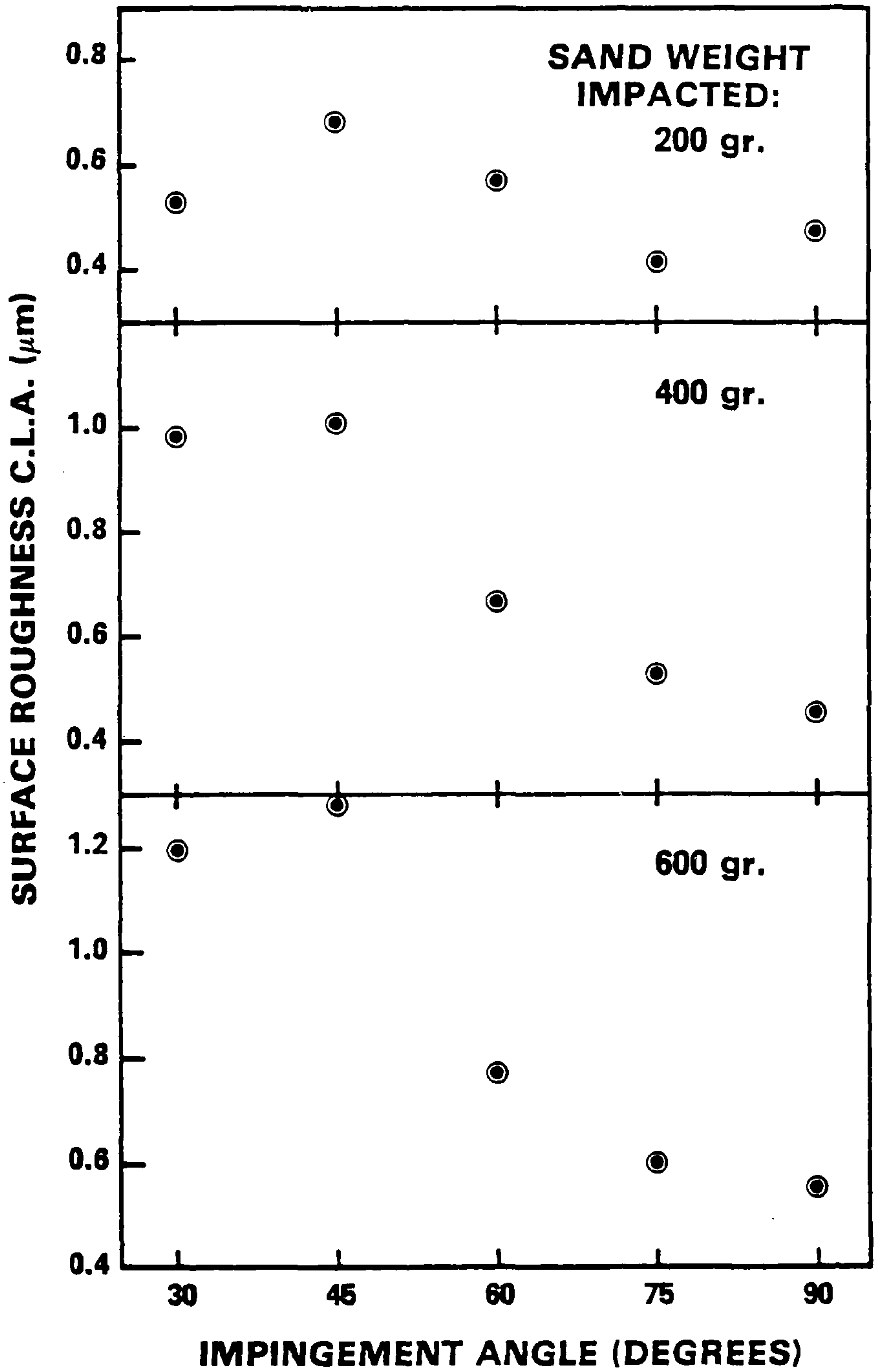


Fig. 3.17 Surface Roughness of Polyurethane Coating of Type "B" as a Function of Impact Angle of Eroding Sand at 42 [m/sec].

3.2.1.3 Polyurethane Coatings "C". A dependence of target surface roughness on impingement angle for constant amounts of sand at constant impact velocity of 42 m/sec is shown in Fig 3.18. Maximum roughness in the range of 0.8-1.4 microns was found at impact angle of 45°. Increasing the impact angle resulted in roughness decrease up to around 0.5 micron at normal impact angle (Fig 3.18).

3.3 Microscopic Observations

Characterization of the various eroded surfaces was carried out through optical microscopy as well as Scanning Electron Microscopy. The results obtained are described herein.

3.3.1 Optical Microscopy

3.3.1.1 Polyurethane Coatings on Glass Epoxy. General appearance of eroded coatings surfaces under various erosion condition is shown in Figs 3.19 and 3.20. In Fig 3.19 the surface morphology of coatings "A", "B" and "C" is shown after being exposed to impacted amounts of sand of 200 gr, 400 gr and 600 gr at constant impingement angle of 90° and impact velocity of 42 m/sec. It was found that the eroded areas were in the middle of the specimen exposed surface so that edge effects were eliminated. Furthermore, visual examination of the various eroded areas (Fig 3.19) did not reveal coatings removal or peeling off under the erosion condition employed.

Figure 3.20 shows the eroded surface of coatings "A", "B" and "C" after being exposed to constant amounts of 200 gr sand particles at impact angles of 30°, 60° and 90° at constant velocity of 42 m/sec. The appearance of grey eroded areas in the middle of the specimen probably corresponded to material removal as well as to the embedment of sand particles onto the surface. Increasing the impact angle resulted in the appearance of intensified grey areas. This was probably due to higher amounts of sand particles being incorporated into the surface. This could also be deduced from the kinetic curves (Figs 3.1 to 3.5).

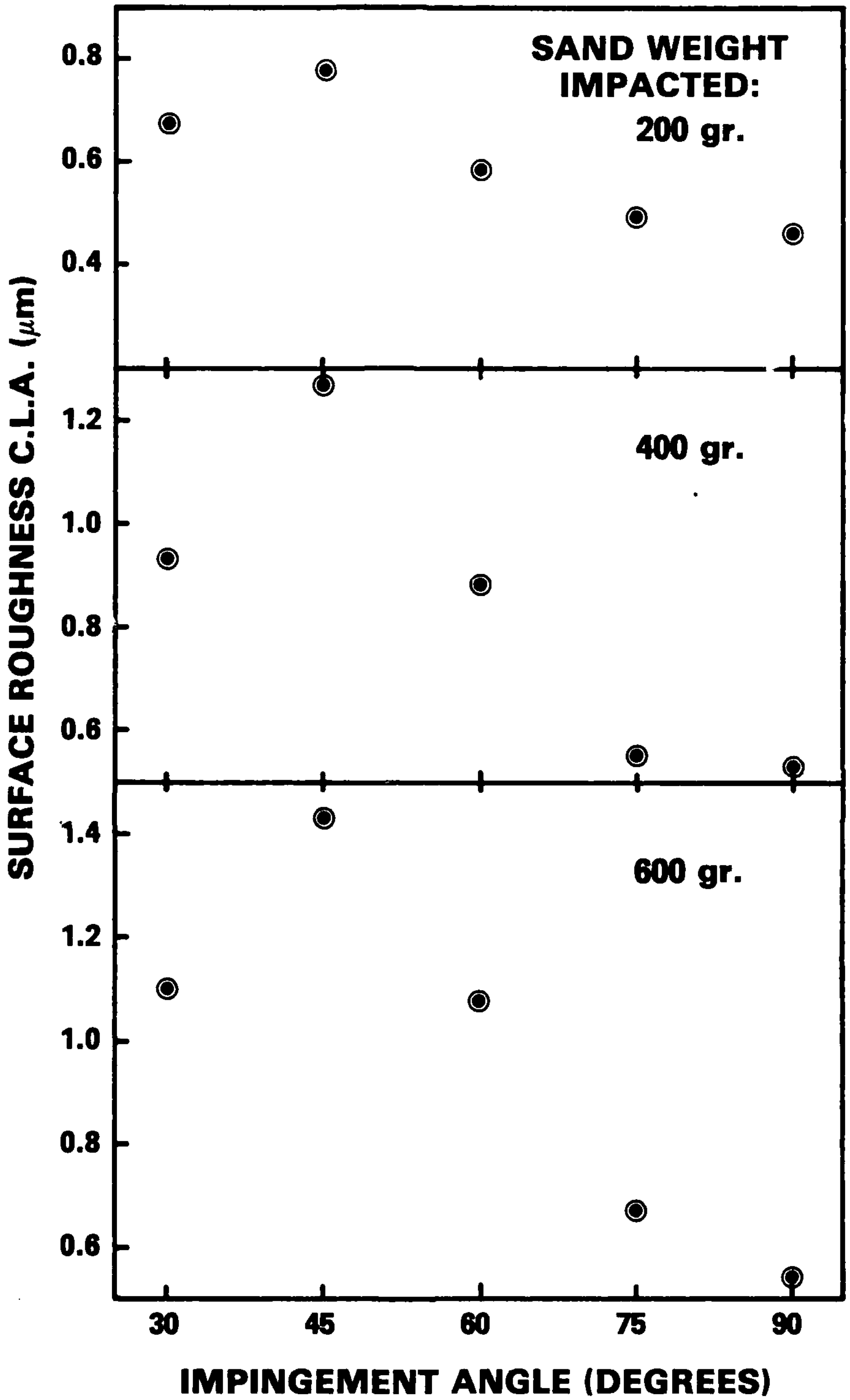


Fig. 3.18 Surface Roughness of Polyurethane Coating of Type "C" as a Function of Impact Angle of Eroding Sand at 42 [m/sec].

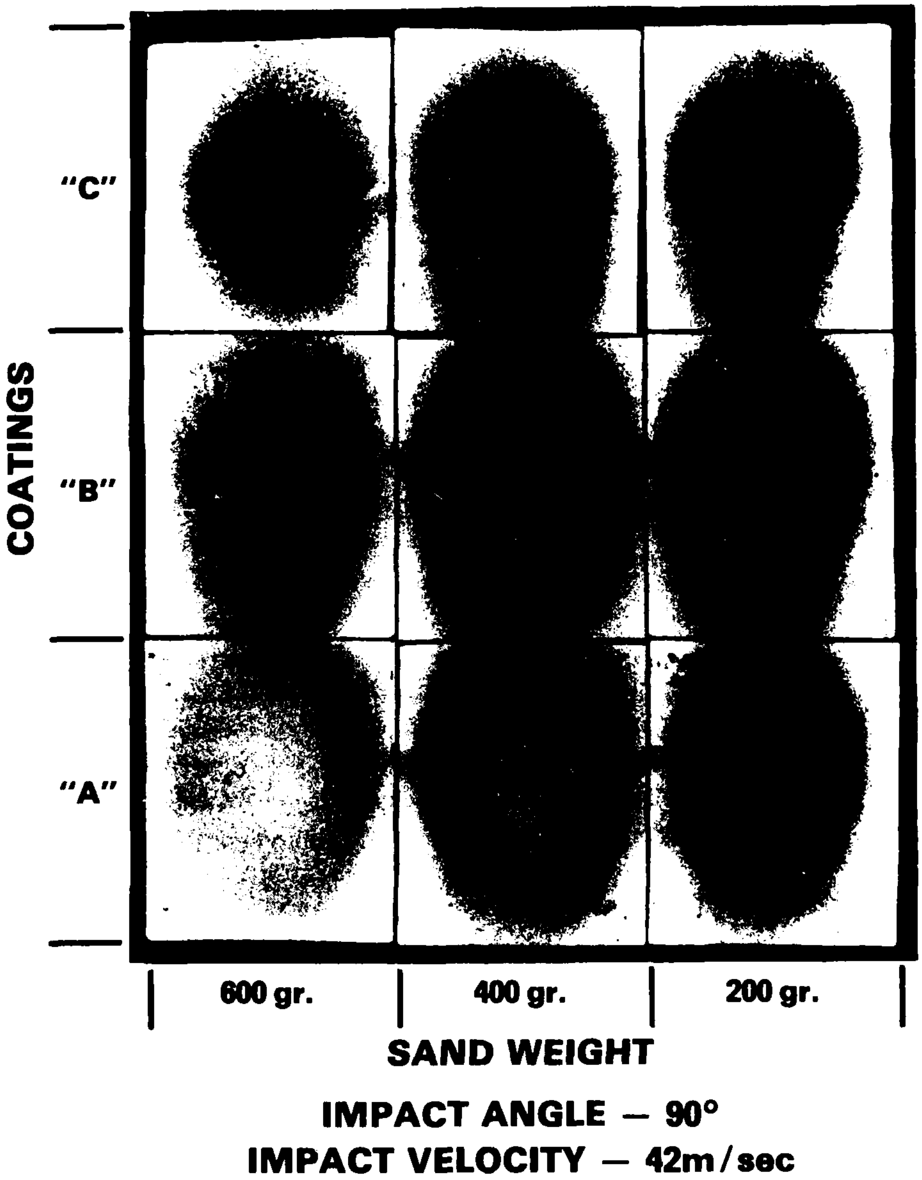


Fig. 3.19 Eroded Surface of Polyurethane Coatings Types "A", "B" and "C" Exposed to 200 gr, 400 gr and 600 gr Amounts of Sand Impacted at Impingement Angle of 90 Degrees and Impact Velocity of 42 [m/sec] Optical Micrographs.

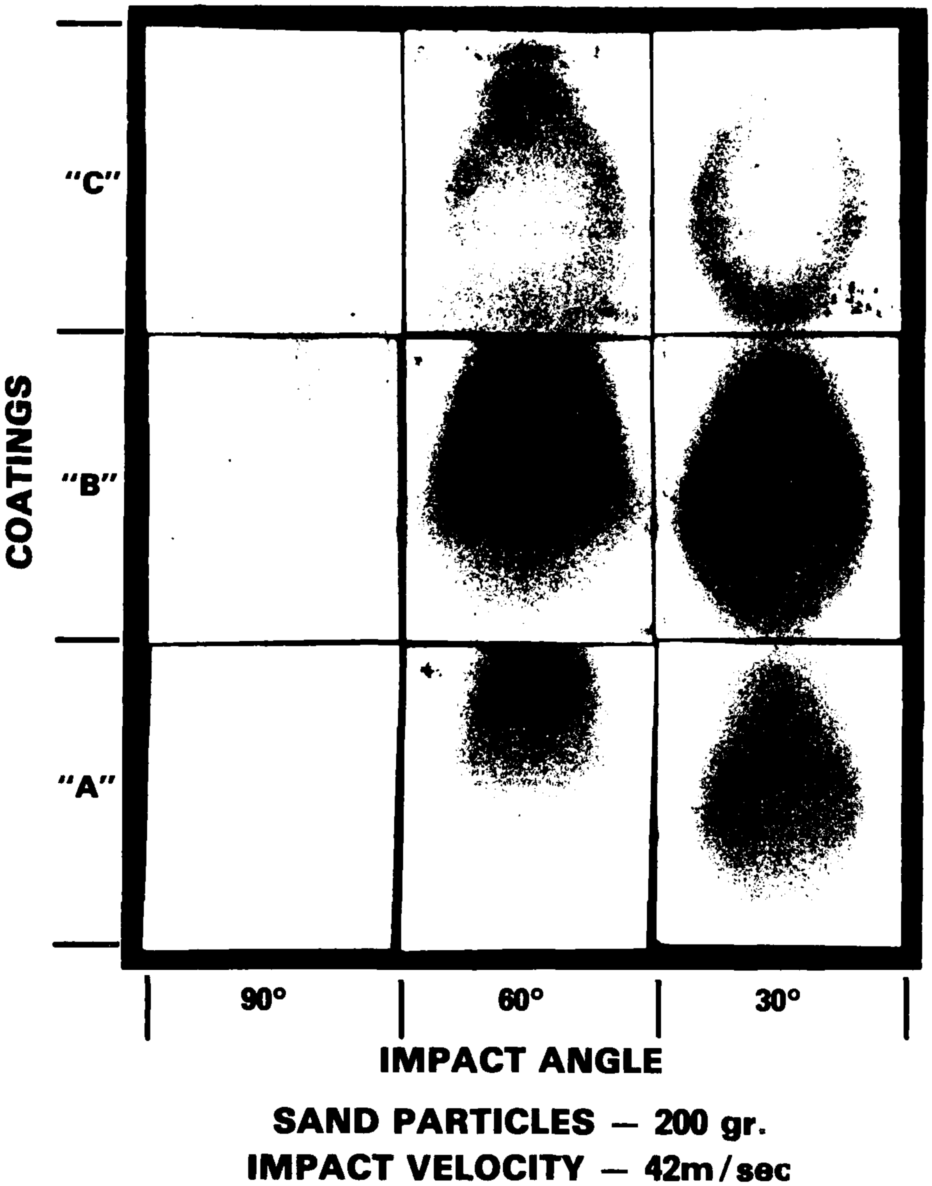


Fig. 3.20 Eroded Surface of Polyurethane Coatings Types "A", "B" and "C" Exposed to 200 gr of Impacted Sand at Impact Velocity of 42 [m/sec] and Impingement Angles of 30, 60 and 90 Degrees Optical Micrographs.

3.3.1.2 Uncoated Reinforced Polyethylene Terephthalate Composite. Optical observations of eroded targets of polyehylene Terephthalate reinforced with T-300 carbon fibers and E-Glass cloth are shown in Figs 3.21, 3.22 and 3.23, respectively. Severe erosion damage was optically detected in the polyethylene Terephthalate containing T-300 carbon fibers (specimen "D") after being exposed to various erosion conditions at impact velocity of 42 m/sec and 74.5 m/sec, as shown in Figs 3.21 and 3.22, respectively. Furthermore, exposure of specimen "D" to 400 gr impacted sand at normal incident angle at 74.5 m/sec resulted in forming a hole in the specimen, as shown in Fig 3.22.

Exposure of polyethylene Terephthalate reinforced with E-Glass cloth fibers (specimen "E") to erosion condition resulted in severe damage to the material as clearly shown in Fig 3.23. At impact angle of 90° and 600 gr sand impacted at 42 m/sec, a complete destruction of specimen "E" was observed (Fig 3.23). The development of surface damage with increasing impact angle corresponded to the weight loss measurements of specimens "D" and "E" with maximum at normal incident impact angle (Figs 3.12, 3.13).

3.3.2 Scanning Electron Microscopy (S.E.M). SEM has been used for detailed characterization of eroded surface, its morphology and structure. The results obtained for the various polyurethane coatings on glass epoxy substrate and for the non-coated reinforced polyethylene Terephthalate are summarized and shown herein.

3.3.2.1 Polyurethane Coatings on Glass Epoxy Composite. Typical eroded surfaces of polyurethane coatings "A" are shown in Figs 3.24 and 3.25 for 200 gr sand impacted at 30° and for 600 gr sand impacted at 90°, respectively. Fig 3.24 shows that the impact of 200 gr sand resulted in local coating removal (Fig 3.24A) as well as the initial exposure and breakage of the E-Glass fibers in the eroded surface. Also, fragments of sand particles were detected in the eroded surface. These were the bright particles 10 μm across, as shown in Fig 3.24C.

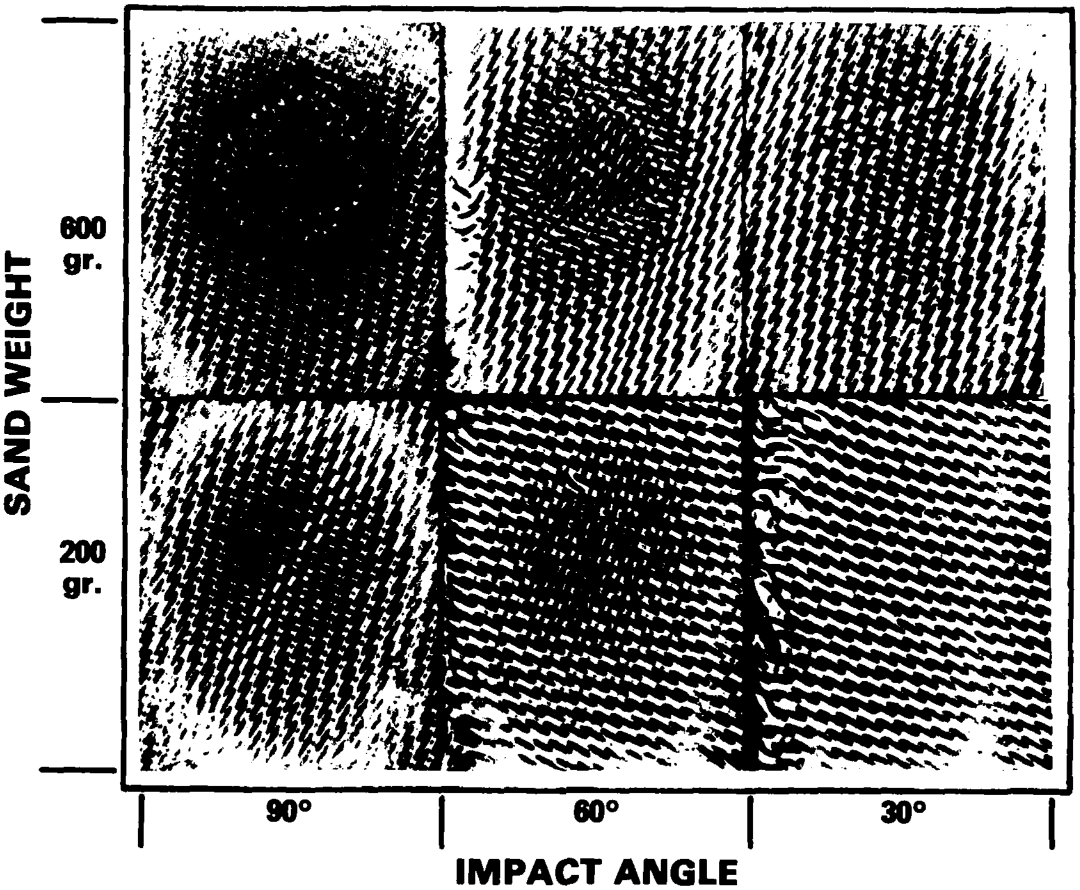


Fig. 3.21 Eroded Surfaces of Composite Material of Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers After Being Exposed to Sand Amounts of 200 gr and 600 gr at Impingement Angles of 30, 60 and 90 Degrees at Constant Velocity of 42 [m/sec].

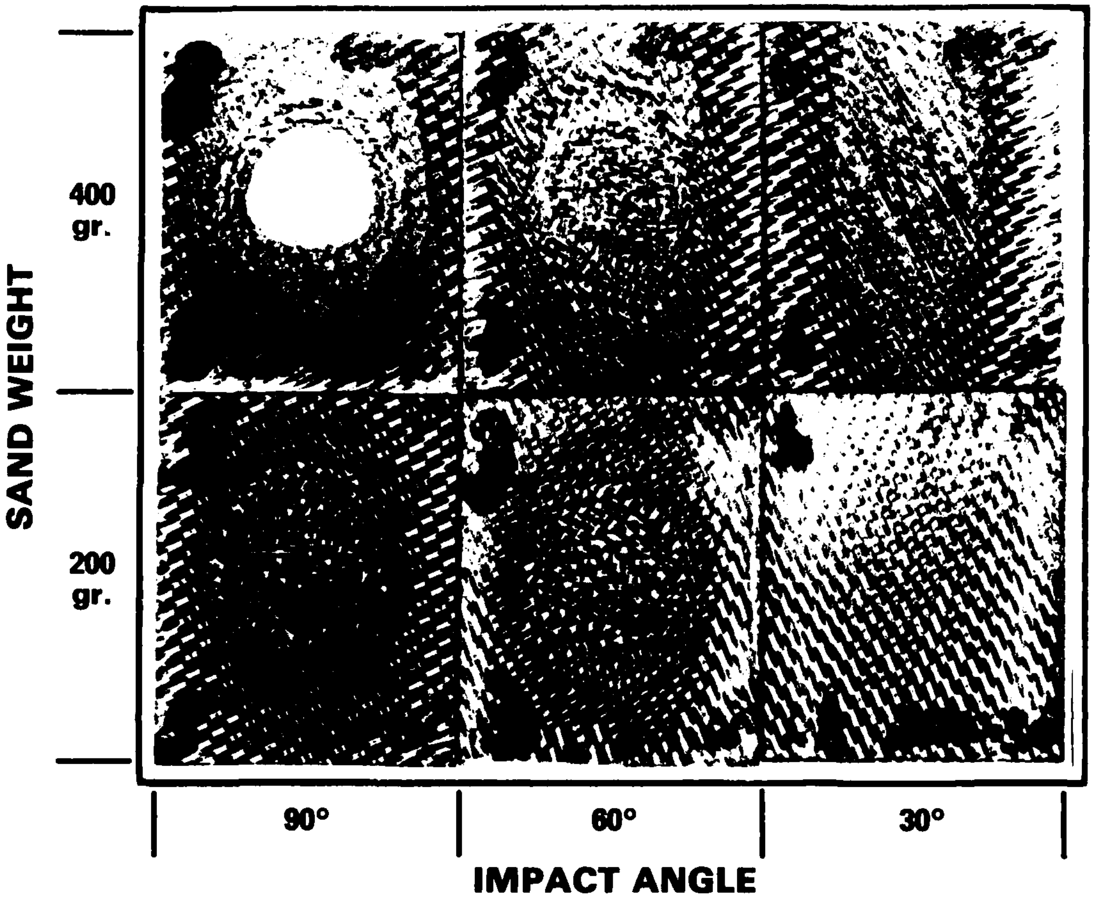


Fig. 3.22 Eroded Surfaces of Composite Material of Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers After Being Exposed to Sand Amounts of 200 gr and 400 gr at Impingement Angles of 30, 60 and 90 Degrees at Constant Velocity at 74.5 [m/sec].

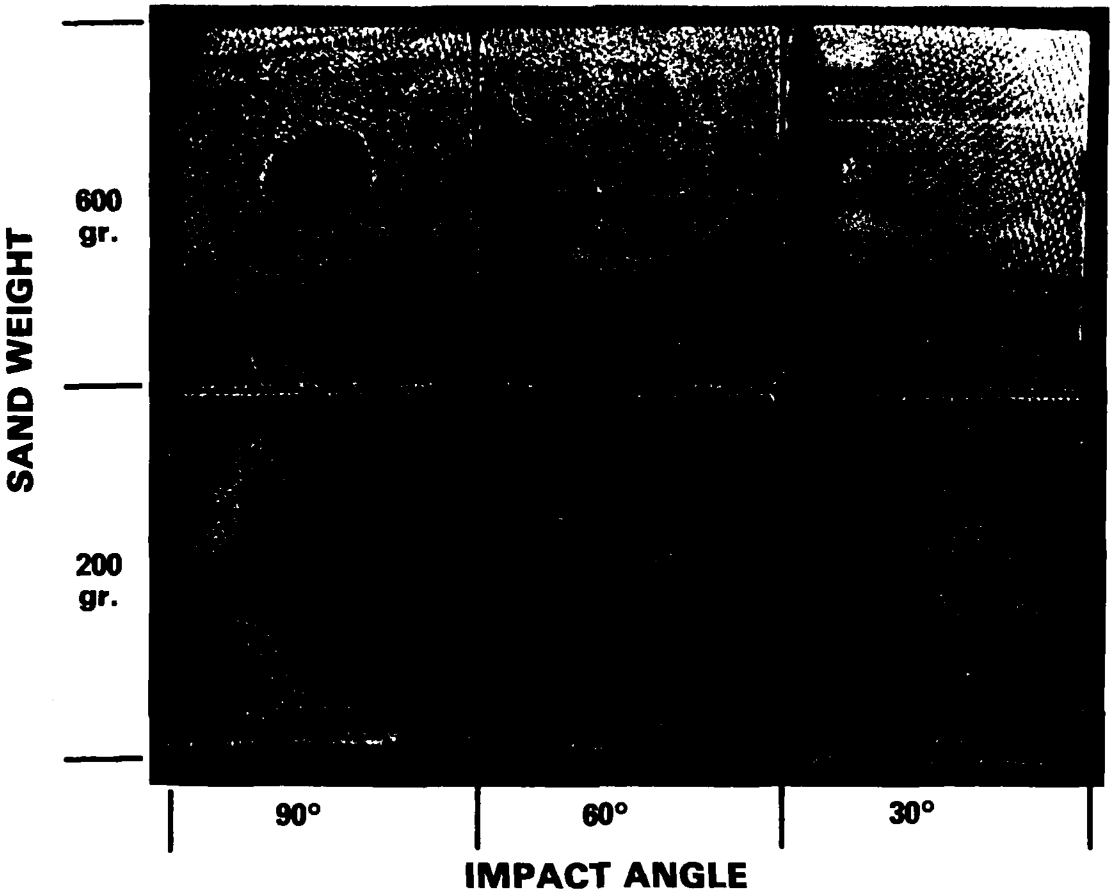


Fig. 3.23 Eroded Surfaces of Composite Material of Polyethylene Terephthalate Reinforced with E Glass Cloth Fibers After Being Exposed to Sand Amounts of 200 gr and 600 gr at Impingement Angles of 30, 60 and 90 Degrees at Constant Velocity of 42 [m/sec].

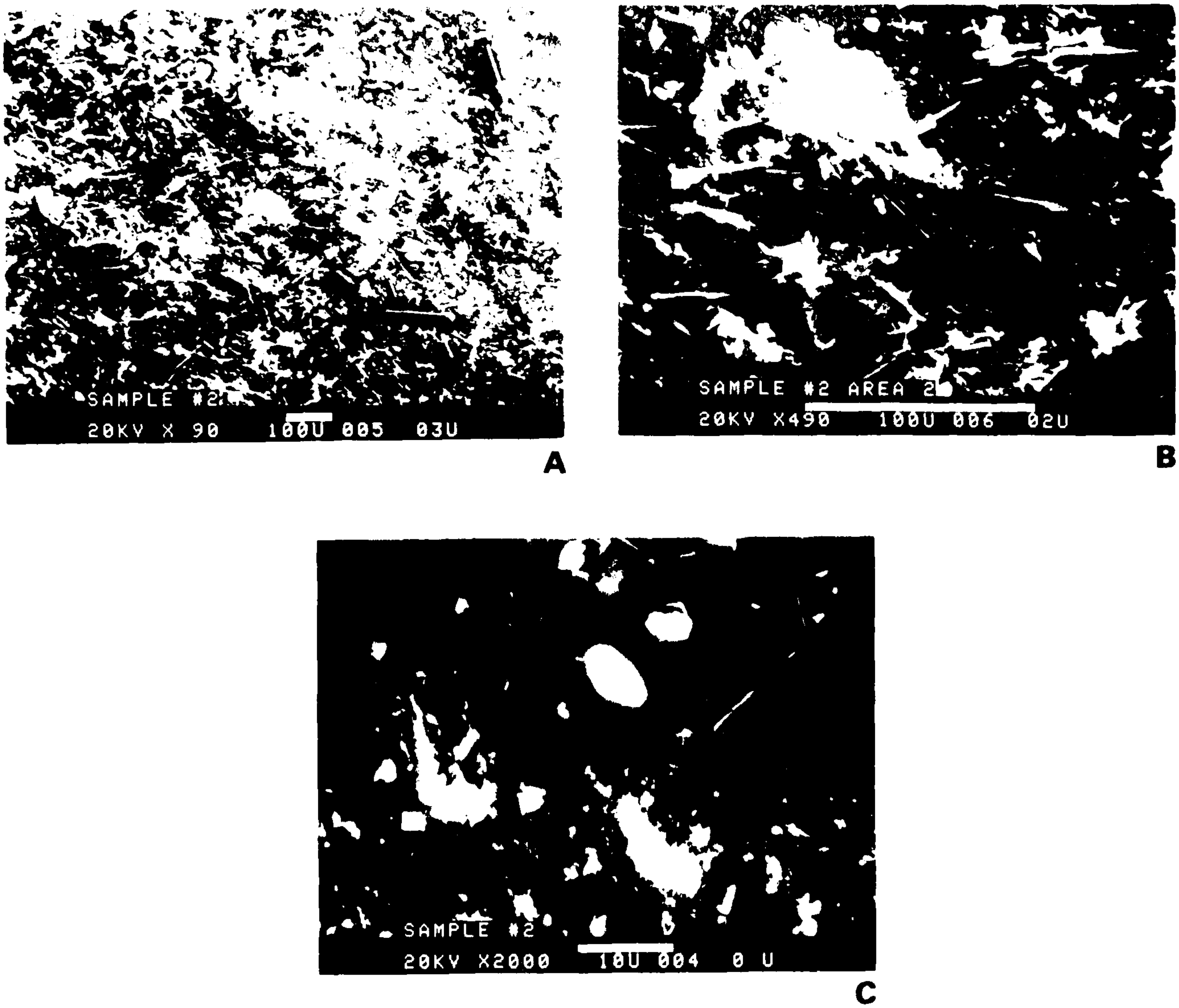


Fig. 3.24 S.E.M. Micrographs of Polyurethane Coating of Type "A" on E Glass Epoxy Substrate After Exposure to 200 gr of Sand Impacted at Impingement Angle of 30 Degrees. (A) General View x 90. (B) Enlargement of A x 490. (C) Enlargement of B x 2000.

Exposure of the polyurethane coatings "A" to 600 gr sand particles at normal incident angle resulted in local coating removal, revealing and breaking the substrate glass fibers as found in Fig 3.25. Detailed damage of the coatings together with fiber breakage could be seen very clearly in Figs 3.25C and 3.25D. Also, fragments of sand particles were observed on the eroded surfaces. These appeared as bright particles about 10 μm across Figs 3.25C and 3.25D.

Figure 3.26 shows the morphology of polyurethane coatings "B" after being exposed to 200 gr sand at 30° at 42 m/sec. Erosion damage of the coating surface was characterized by local processes of coating removal in the range of up to 5 μm in size. No peeling off or exposure of fibers or their breakage were observed (Fig 3.26B), not even at high magnification (Figs 3.26C, 3.26D) However, some sand fragments were embedded in the eroded surface, as shown in Fig 3.26D (bright particles about 0.5μm at the right hand side of the picture).

The morphology of polyurethane coatings "C" impacted with 600 gr sand particles at 90° incident angle is shown in Fig 3.27. The typical general view of the eroded coating surface is shown in Figs 3.27A and 3.27B. A complete coverage of the glass epoxy substrate by the polyurethane coating "C" was found (Fig 3.27A, B). Basically under these erosion conditions no significant coating materials was removed. However, looking at the surface at high magnification, one could observe the formation of microcracks in the coating as shown in Fig 3.27C.

3.3.2.2 <u>Uncoated Polyethylene Terephthalate Reinforced Composite</u>.

3.3.2.2.1 <u>Polyethylene Terephthalate Reinforced with T-300 Carbon Fibers (Specimen "D")</u>. SEM observations of eroded specimens "D" are shown in Figs 3.28, 3.29, for 600 gr sand impacted at 42 m/sec and at incident angle of 30° and 90°, respectively. Figures 3.30 and 3.31 show the surface after being exposed to 200 gr sand at 74.5 m/sec and incident impact angles of 90° and 60°, respectively.

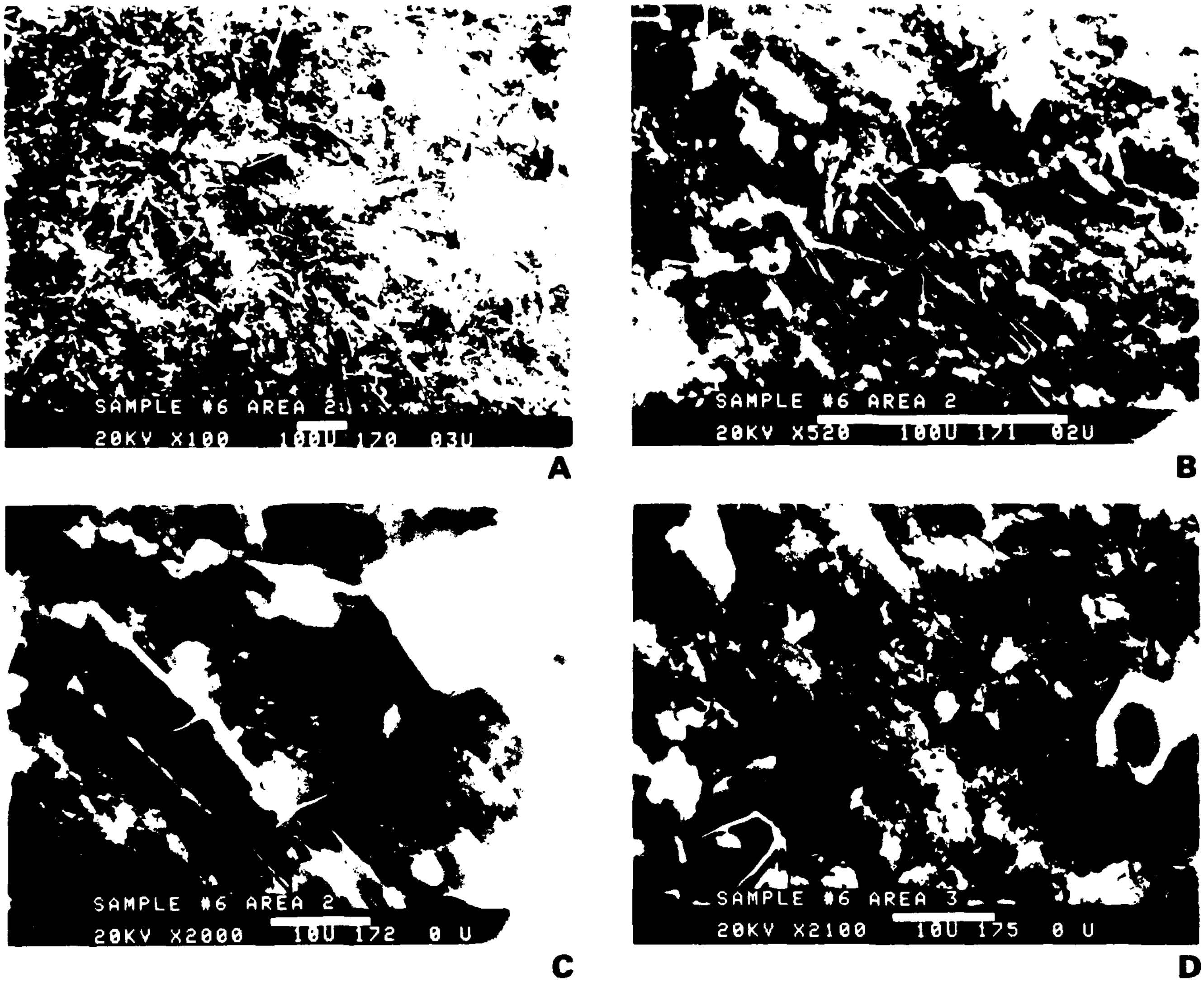


Fig. 3.25 S.E.M. Micrographs of Polyurethane Coating of Type "A" on E Glass Epoxy Substrate After Exposure to 600 gr of Sand Impacted at Impingement Angle of 90 Degrees. (A) General View x 100. (B) Eroded Resin and Fibers x 520. (C) High Magnification of Eroded Fibers x 2000. (D) High Magnification of Eroded Resin Zone x 2100.

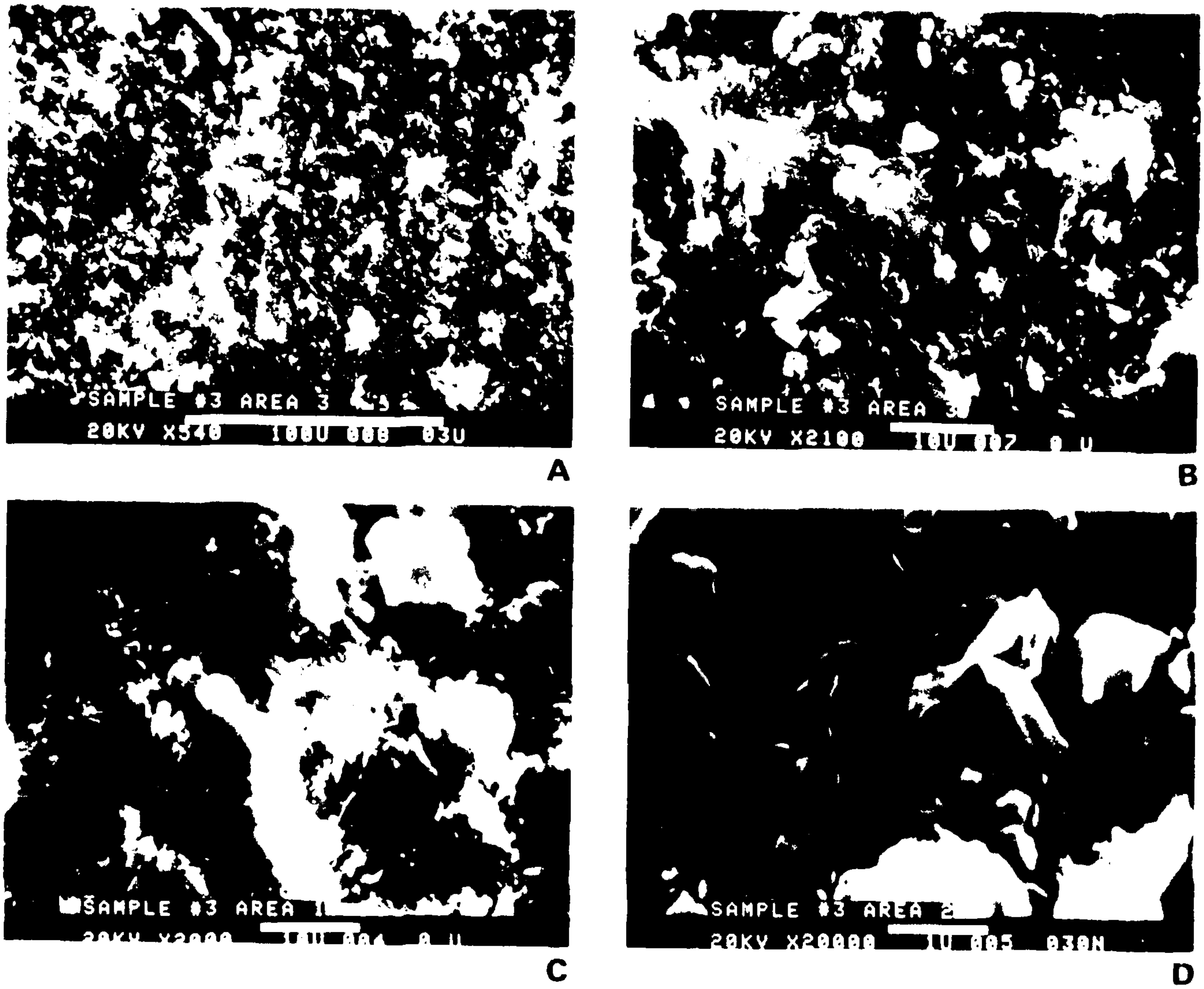


Fig. 5.26 S.E.M. Micrographs of Polyurethane Coating of Type "B" on E Glass Epoxy Substrate After Exposure to 200 gr of Sand Impacted at Impingement Angle of 30 Degrees. (A) General View x 540. (B) Enlargement of A x 2100. (C) High Magnification of Eroded Area Showing the Embedment of Sand Particles x 2000. (D) Very High Magnification of Eroded Area x 20,000.

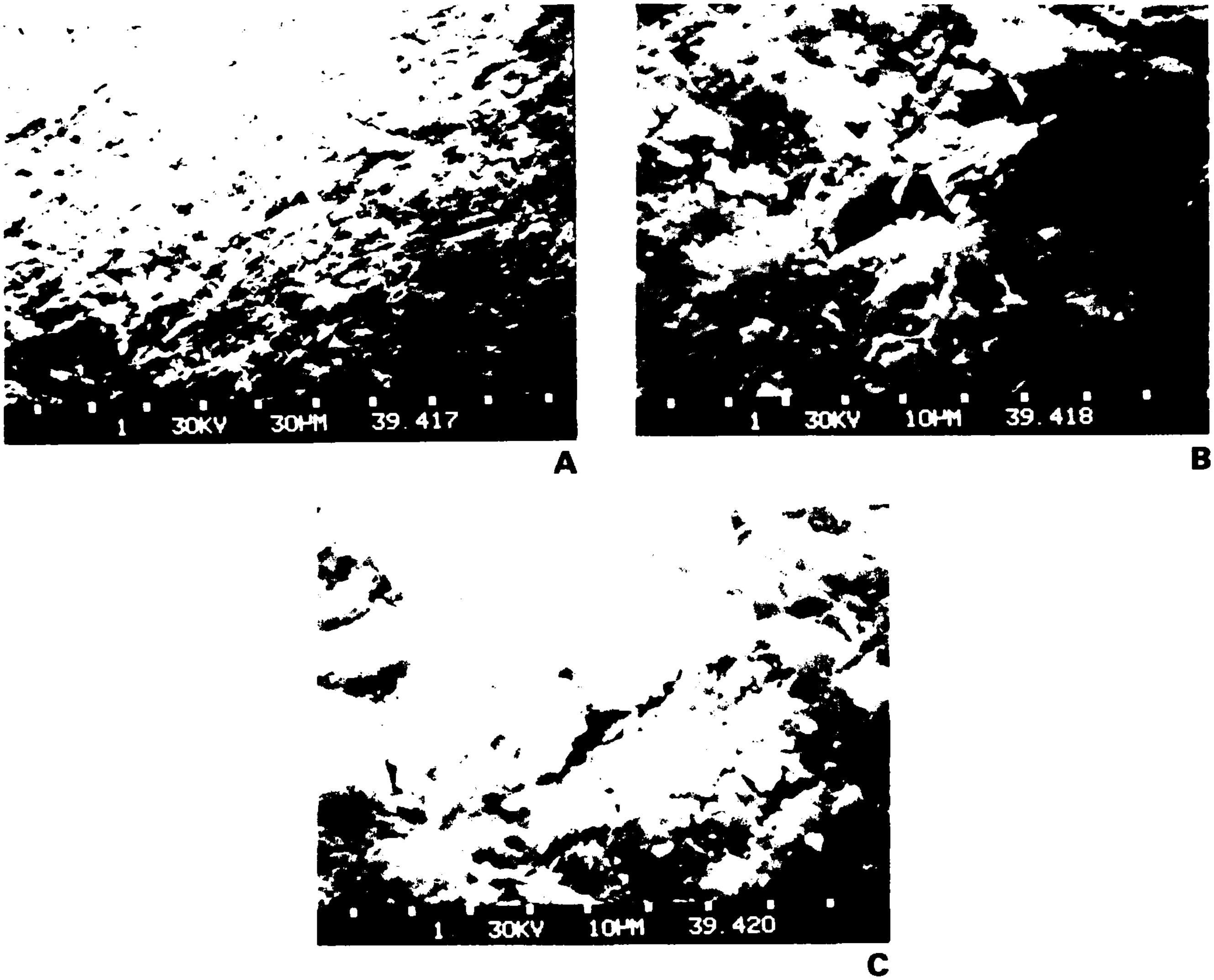


Fig. 3.27 S.E.M. Micrographs of Polyurethane Coating of Type "C" on E Glass Epoxy Substrate After Exposure to 600 gr of Sand Impacted at Impingement Angle of 90 Degrees. (A) General View of the Eroded Coating x 300. (B) Enlargement of Area A Showing Embedment of Sand Particles as Well as Initial Formation of Microcracks x 1000. (C) High Magnification of Other Zone Showing the Initiation and Propagation of Microcracks x 1000.

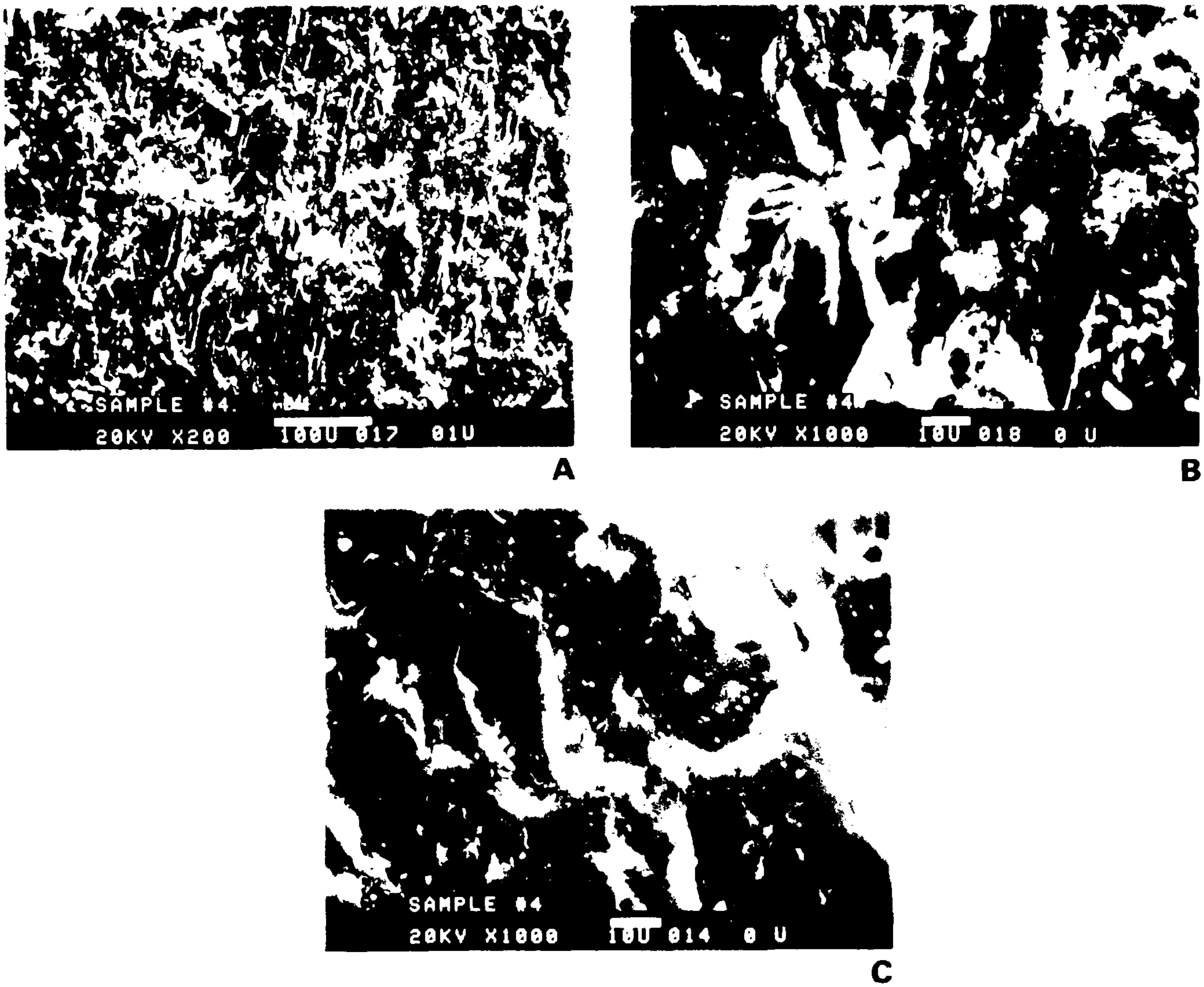


Fig. 3.28 S.E.M. Micrographs of Polyethylene Terephthalate Containing T-300 Carbon Fibers (Specimen "D") After 600 gr Sand Impacted at 30 Degrees at 42 m/sec. (A) General Appearance of Eroded Area x 200. (B) Eroded Area Showing Breakage of Fibers x 1000. (C) High Magnification of Other Eroded Area x 1000.

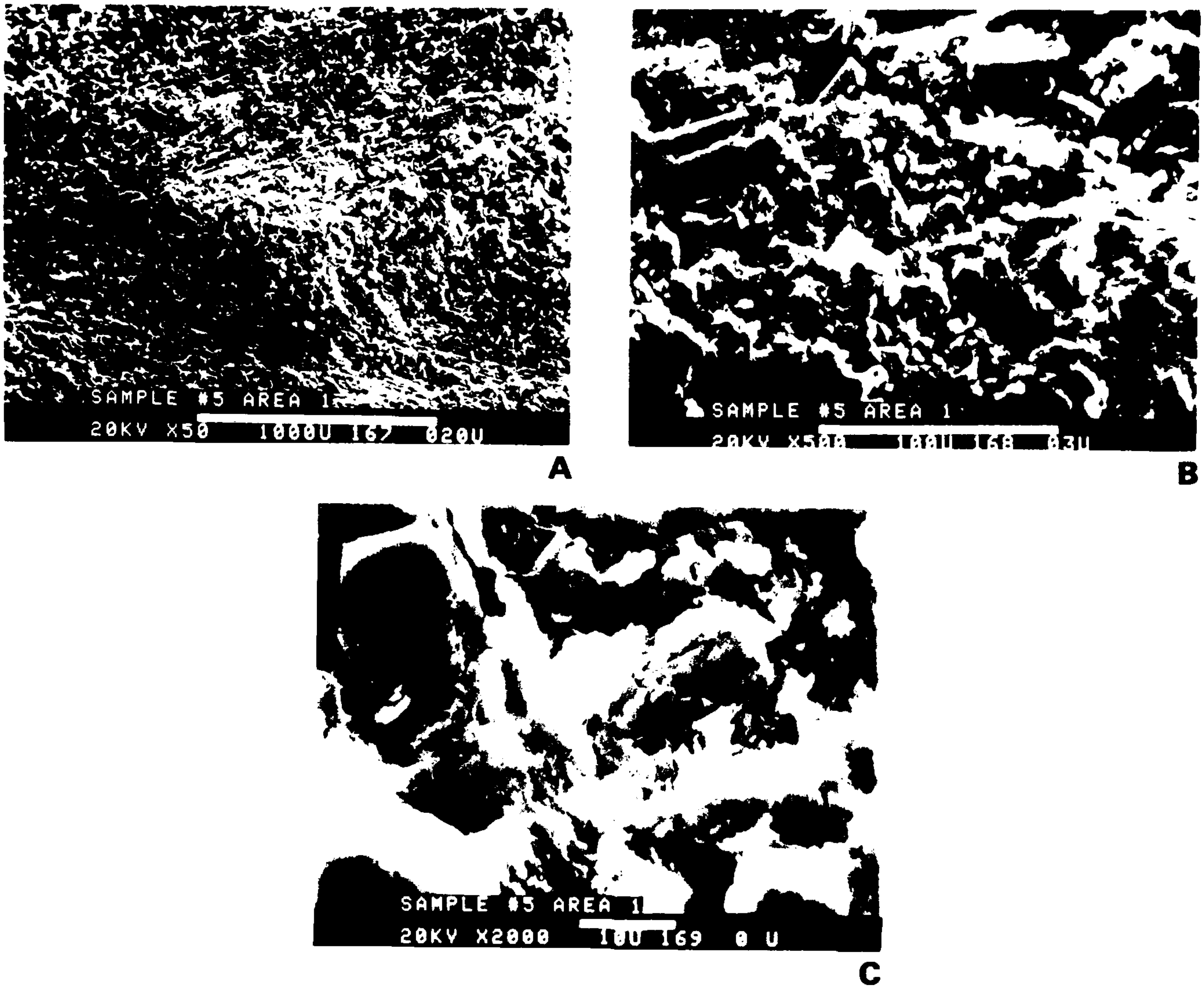


Fig. 3.29 S.E.M. Micrographs of Polyethylene Terephthalate Containing T-300 Carbon Fibers (Specimen "D") After 600 gr Sand Impacted at 90 Degrees at 42 m/sec. (A) General View of the Eroded Area x 50. (B) High Magnification View of Eroded Area x 500. (C) Higher Magnification of Eroded Area Showing Fiber Breakage and Removal of Resin Material x 2000.

The mode of erosion damage found in specimen "D" after being exposed to erosion at impact velocity of 42 m/sec was characterized by removal of resin materials, exposure of the carbon fibers as well as breakage of them as observed in Figs 3.28 and 3.29 at various magnifications. Fig 3.29 shows severe damage to the resin material and to the fibers when the specimen was exposed to 600 gr sand at impact angle of 90° at 42 m/sec. However, when the specimen was exposed to 600 gr sand at 30°, the major erosion damage resulted from the removal of the resin material with damaging or breakage of most of the carbon fibers, as seen clearly in Figs 3.28A and 3.28B.

Exposure of specimen "D" to impated sand amount of 200 gr at incident angles of 90° and 60° at constant impact velocity of 74.5 m/sec resulted in severe erosion damage to the polyethylene Terephthalate resin as well as to the carbon fibers. This can be seen in Figs 3.30 and 3.31.

Figures 3.23A and B show the general appearance of the eroded surface while Figs 3.30C and 3.30D, respectively, show the mode of erosion damage in the resin and in the fibers themselves.

Figure 3.31A shows the general morphology of the eroded surface (200 gr, 60°), whereas the detailed damage found in the resin material and in the carbon fibers is shown in Figs 3.31B and 3.31C.

3.3.2.2.2 <u>Polyethylene Terephthalate Reinforced with E-Glass Cloth (Specimen "E")</u>. The morphology and structure of eroded surface as observed in scanning electron microscopy (SEM) is shown in Figs 3.32, 3.33 and 3.34 for erosion conditions of 600 gr and 200 gr sand impacted at incident angle of 30° and 90° at constant impact velocity of 42 m/sec. Under the erosion condition investigated, the major erosion damage in specimen "E" was the removal of the resin material (Figs 3.32A, 3.33A 3.34A) as well as the breaking of the glass fibers themselves, as shown in Figs 3.32B, 3.33B and 3.34B.

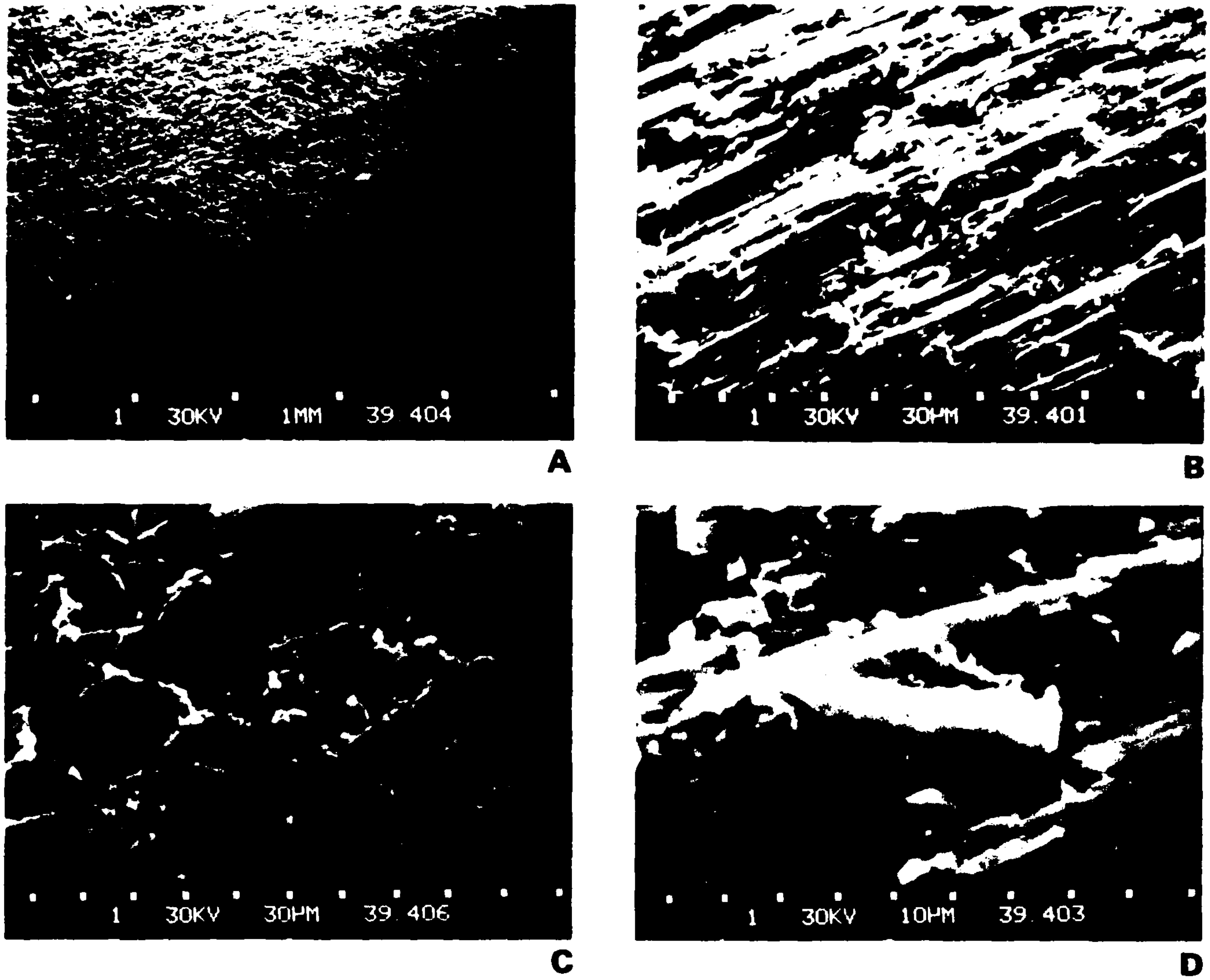
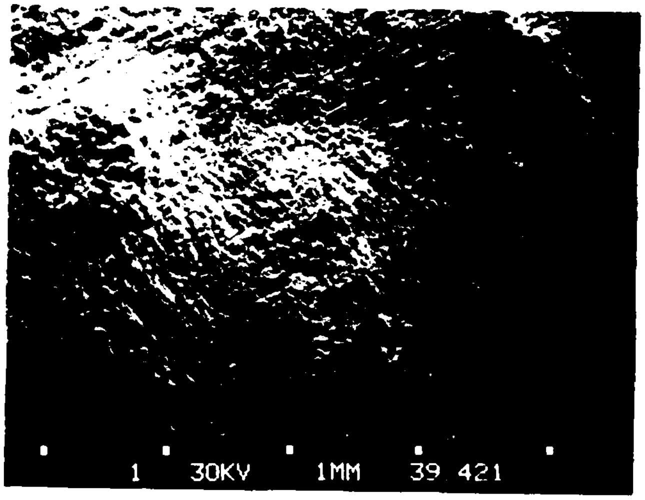
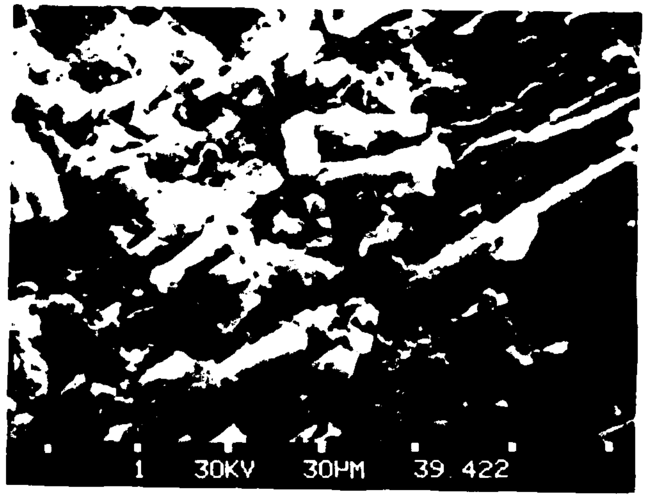


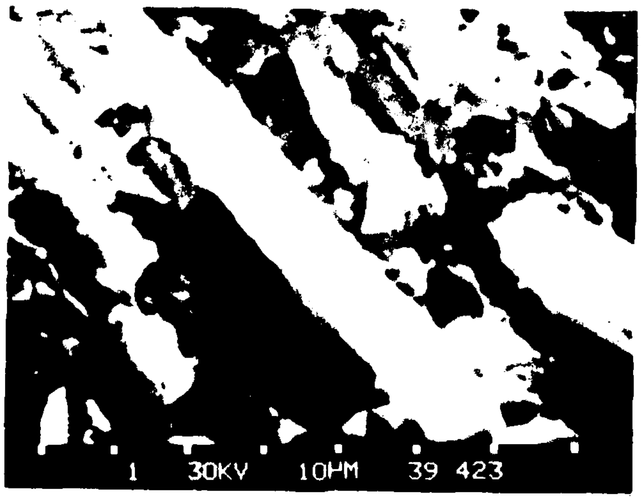
Fig. 3.30 S.E.M. Micrographs of Polyethylene Terephthalate Containing T-300 Carbon Fibers (Specimen "D") After 200 gr Sand Impacted at 90 Degrees at 74.5 m/sec. (A) General View of the Eroded Area x 50. (B) High Magnification View of Eroded Area x 500. (C) Higher Magnification of Eroded Area Showing Fiber Breakage and Removal of Resin Material x 2000.



A



B



C

Fig. 3.31 S.E.M. Micrographs of Polyethylene Terephthalate Containing T-300 Carbon Fibers (Specimen "D") After 200 gr Sand Impacted at 60 Degrees at 74.5 m/sec. (A) General View of the Eroded Area x 20. (B) Eroded Area with Broken Fibers x 500. (C) High Magnification of Eroded Area Showing Fibers and Broken Fibers x 1200.

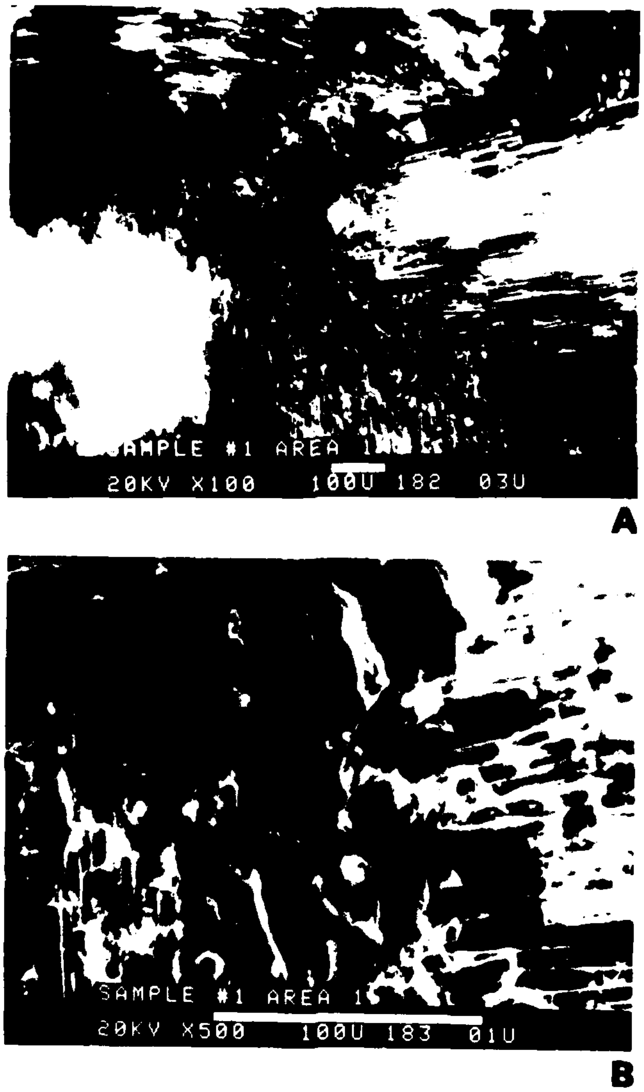
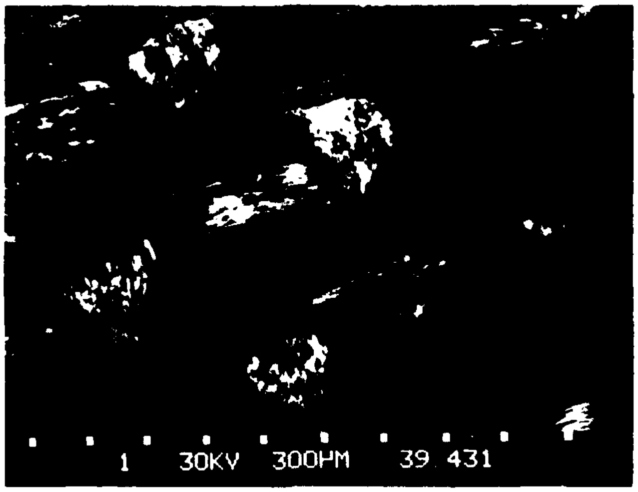
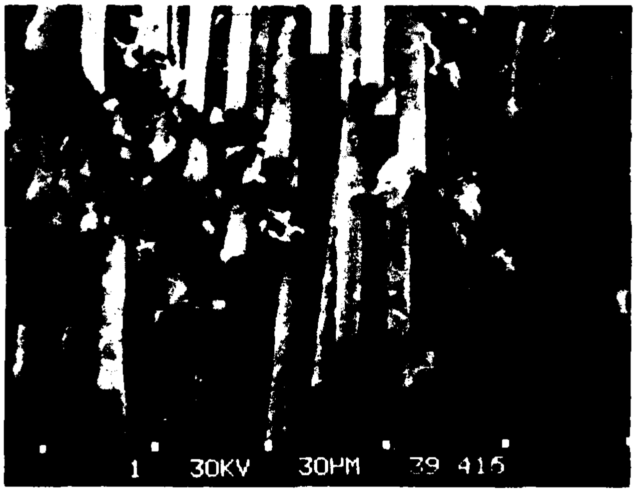


Fig. 3.32 S.E.M. Micrographs of Polyethylene Terephthalate Containing E Glass Fibers (Specimen "E") After 600 gr Sand Impacted at 30 Degrees at 42 m/sec. (A) General View of Eroded Area x 100. (B) High Magnification of Eroded Area Showing Broken Fibers x 500.

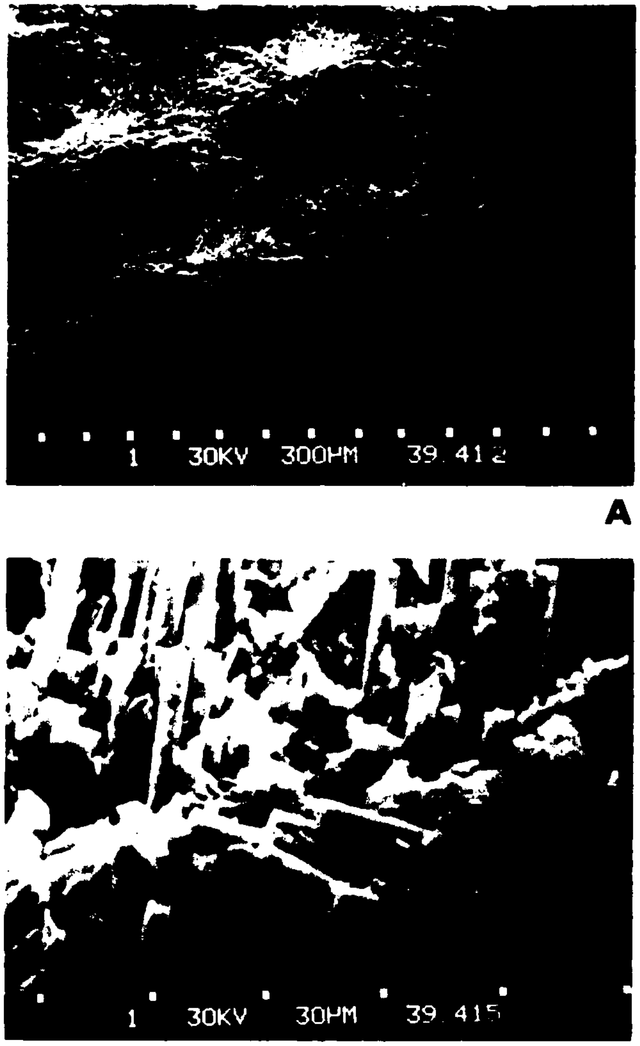


A



B

Fig. 3.33 S.E.M. Micrographs of Polyethylene Terephthalate Containing E Glass Fibers (Specimen "E") After 200 gr Sand Impacted at 300 Degrees at 42 m/sec. (A) General View of the Eroded Area x 30. (B) High Magnification of Eroded Area Showing Broken Fibers x 600.



A

B

Fig. 3.34 S.E.M. Micrographs of Polyethylene Terephthalate Contain-E Glass Fibers (Specimen "E") After 200 gr Sand Impacted at 90 Degrees at 42 m/sec. (A) General View of Eroded Area x 20. (B) High Magnification of Eroded Area Showing Broken Fibers x 600.

4. DISCUSSION

4.1 Polyurethane Coatings on Glass Epoxy Substrate.

Various experimental methods have been used in this study for characterization of the erosion processes and damage introduced by impingement of solid particles on polyurethane coatings on glass epoxy substrate. These methods consisted of target weight change, surface roughness and surface structure and morphology.

4.1.1 Effect of Angle and Sand Weight Impacted.

The sand erosion behavior of the various polyurethane coatings "A", "B", "C" as well as "AB" and "AC" on glass epoxy composite substrate was affected substantially by the impact angle. The coatings exhibited ductile behavior wherein maximum erosion, expressed as target weight change, was found at a low incident angle of 30° while the minimum erosion occurred at normal angle (Figs 3.1-3.6). Furthermore, all the ployurethane coatings exhibited zero weight change at incident impact angle in the range of 35-50° for the total amount of sand particles used (200 to 600 gr). At impact angles below the range of 35-50° target weight loss was found; whereas, above that range of impact angles, target weight gain was gound. Generally, target weight loss increased with the additional amount of sand impacted at low angles (below 35-50°). At high impact angles (above 50°) target weight gain was found to increase with the additional amounts of sand impacted. (See Figs 3.7 to 3.11.)

The effect of impact angles on sand erosion behavior of polyurethane coatings at high impact velocity of 74.5 m/sec, compared to 42.0 m/sec, were basically the same as shown in Figs 3.1 and 3.2, respectively. Maximum erosion or target weight loss was found at the low incident angle of 30°. Increasing the impact angle resulted in a decrease of the target weight reaching a minimum value at normal incident angle (Fig 3.2). That behavior signifies a ductile type response of the polyurethane coating at high impact velocities. Furthermore, at that range of velocity (74.5

m/sec), only weight loss was observed, while at the lower impact velocity, target weight loss and weight gain were found together (Fig 3.1). That different behavior could be explained by the fact that at the lower velocity range more fragments of sand particles were embedded onto the eroded coating surface as compared to the amount embedded at higher velocities under the same erosion conditi ns.

4.1.2 Effects of Surface Roughness and Morphology. Sand erosion behavior studies of the various types of polyurethane coatings showed an interrelationship among erosion rate, impact angles and coatings surface morphology and roughness. The polyurethane coatings showed maximum erosion, i.e., weight loss, at low incident angles (Figs 3.1 to 3.6). When maximum weight loss was found, a maximum surface roughness was observed. High surface roughness of eroded coatings was measured at low incident angles for various constant amounts of sand impacted (Figs 3.15-3.18). Furthermore, increases in sand impact angle resulted in decrease of target weight loss and in a simultaneous decrease of coating surface roughness.

The mode through which the erosion processes took place on coating surfaces was investigated by microscopic observations. The processes of coatings sand erosion were characterized by localized removal of polyurethane coating material from the eroded surfaces (Figs 3.24 to 3.27). These processes were associated with initial formation of microcracks in the coatings (Fig 3.27). These were then propogated, intersecting each other, causing the formation of local coating fragments (up to 10 microns in size) which were then removed exposing the composite substrate to erosive environment, both at low and high impact angles (Figs 3.24-3.27). Once coatings fragments were detected from the surface, erosion processes took place at the composite substrate resulting in fiber detachment from the resin matrix and breakage of fibers (Figs 3.24, 3.25). Moreover, the erosion processes, namely surface material removal, were associated with embedment of sand fragment particles (10μm in size) onto the impinged surface. The entrapment of these sand particles onto the eroded surfaces were believed to be the main factors causing target weight gain under various erosion conditions particularly at impact angles above 45° (Fig 3.25D).

4.1.3 Effect of Polyurethane Coatings Type. Several types of polyurethane coatings were tested under various sand erosion conditions and their behavior was investigated in this work. The compositions and properties of these various coatings, designated as coating "A", "B", "C", "AB" and "AC" are described in section 2.2 of this report. Coatings "A", "B", and "C" differed from each other in their composition; namely, the NCO/OH ratios which resulted in their tensile modulus differences.

From studies of the dependence of sand erosion impact angle and mass of sand impacted on polyurethane coating target weight loss, it was found that the coatings of type "A", "B", "C", "AB" and "AC" on glass epoxy were affected substantially (Figs 3.1 to 3.6). All these types of coatings exhibited the same behavior under similar erosion conditions; namely, they showed maximum target weight loss at a low impact angle of 30° and increase of target weight loss with mass of sand impacted. Furthermore, no major differences either in the erosion behavior or in the dependence of surface roughness or impact angle were found in the various types of the polyurethane coatings used in this study. Similar sand erosion behavior of polyurethane coatings (MIL-C-83231) on glass epoxy substrate has been previously found by these authors[1,2].

4.2 Composite Materials of Polyethylene Terephthalate Reinforced with (A) T-300 Carbon Fibers and (B) E Glass Cloth.

The behavior of the composite material specimen was characterized by target weight change surface roughness and surface structure and morphology.

4.2.1 Effects of Impingement Angle and Sand Weight Impacted. For the polyethylene Terephthalate composites containing either T-300 carbon fibers or E-glass fibers, it was found that there was a progressive increase of erosion which was in direct relationship to the increase of the impact angle (Fig 3.13) and the mass of sand impacted (Fig 3.14).

In a comparison of polyethylene Terephthalate (PET), containing E glass fibers, with epoxy containing E-glass fibers[1,2] under the same erosion condition, it was found that the PET composite eroded about ten times as much as the epoxy composite[1,2]. Probably the difference in the erosion could be related to the difference in the erosion of the resin matrix, namely, higher erosion rate of the PET (thermoplastic matrix) as compared to the epoxy (thermoset material) assuming that the E-glass fibers behaved similarly in the two resin matrices. Similar behavior was observed in rain erosion exposure of reinforced thermoplastic and thermoset composites by Schmitt (Ref. 5). However, although the fibers themselves might behave and show the same erosion resistance, their adhesion and compatibility to the matrix materials might be different; and, in that case, might partially explain the difference in the erosion resistance of the two composites.

In comparing the PET containing the T-300 carbon fibers with the PET containing the E-glass fibers, it was found that, although their erosion behavior was similar, the weight loss or the erosion of the PET containing the glass fiber was about three times as much as the PET containing the carbon fibers (Fig 3.13).

4.2.2 Effects of Surface Morphology and Structure. Eroded surface morphology and structure revealed by optical and SEM observations are shown in Figs 3.21, 3.23 and in Figs 3.29, 3.30, 3.31, respectively. The amount of erosion observed in the PET containing E glass fibers was higher compared to PET containing carbon fibers as could be seen by visual inspection (Fig 3.20 compared with Fig 3.23). Furthermore, a detailed microscopic observation showed substantial severe erosion damage in the E glass fibers compared to carbon fibers (Figs 3.31 and 3.33). The damage was characterized by breakage of the fibers and consequently their removal, which resulted in higher target weight loss in the PET containing the glass fibers (Fig 3.13).

5. CONCLUSIONS

The observations and the results obtained and described in this work led to the following major conclusions.

5.1 Polyurethane Coatings

5.1.1 In all coatings investigated, erosion (i.e., target weight loss) decreased with the increase of the impact angle. Maximum weight loss was found at 30° while minimum value of weight loss was found at normal impact angle.

5.1.2 A progressive increase in target coating weight loss with amount of sand impacted was found in all the polyurethane coatings at constant impact angles.

5.1.3 Eroded polyurethane coatings surface roughness was found to follow target weight loss; the higher the weight loss the higher the value of surface roughness observed.

5.1.4 Erosion processes in the coatings were associated with formation of microcracks, microcracks propogation and intersection resulting in fragments of coatings which were then locally removed from the surface.

5.1.5 Polyurethane coatings with various ratios of NCO/OH and tensile modulus tested in this work behaved similarly and indicated the same erosion values under the same sand erosion conditions.

5.2 Composite Materials

5.2.1 Erosion, namely target weight loss increased with increasing impact angle reaching maximum at normal incident angle while the lowest erosion value was around 30° for various constant amounts of sand particles impacted.

5.2.2 Target weight loss increased progressively in direct relationship to the increase of sand impacted in the range of 200 gr to 600 gr.

5.2.3 The basic erosion processes taking place in the polyethylene Terephthalate composite materials consisted of the following:

(a) local material removal in the resin zones;

(b) erosion in the fiber zones associated with breaking down the fibers into small fragments;

(c) erosion of the interface zones between fibers and adjacent resin matrix.

5.2.4 Composite materials of polyethylene Terephthalate containing E-glass fibers eroded about three times as much compared to the polyethylene Terephthalate containing T-300 carbon fibers.

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APPENDIX A

EROSION DATA OF

COATED AND NONCOATED COMPOSITE MATERIALS

TABLE A.1

WEIGHT LOSS DATA FOR POLYURETHANE COATING TYPE "A"
IMPACT VELOCITY -- 42 M/SEC

Impact Velocity	Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Target Weight Loss (mg)	Erosion* $\varepsilon . 10^6$
42 m/sec	200	30	2.8	14.0
		45	-0.7	- 3.5
		60	-1.5	- 7.5
		75	-1.3	- 6.5
		90	-1.8	- 9.0
	400	30	2.6	6.5
		45	-0.5	- 1.2
		60	-1.5	- 3.7
		75	-2.1	- 5.2
		90	-2.8	- 7.0
	600	30	0.7	1.2
		45	0.0	0.0
		60	-2.3	- 3.8
		75	-2.9	- 4.8
		90	-3.4	- 5.7

*Amount of material removed; amount of sand impacted

TABLE A.2

WEIGHT LOSS DATA FOR POLYURETHANE COATING TYPE "A"
IMPACT VELOCITY -- 74.5 M/SEC

Impact Velocity	Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Target Weight Loss (mg)	Erosion* $\epsilon.10^6$
74.5 m/sec	200	30	5.1	25.5
		45	1.6	8.0
		60	-1.7	- 8.5
		75	-2.7	-13.5
		90	-2.8	-14.0
	400	30	14.0	35.0
		45	8.2	20.5
		60	- 2.1	- 5.2
		75	- 2.2	- 5.5
		90	- 2.4	- 6.0
	600	30	24.2	40.3
		45		
		60	- 0.3	- 0.5
		75	- 3.0	- 5.0
		90	- 3.2	- 5.3

TABLE A.3

WEIGHT LOSS DATA FOR POLYURETHANE COATING TYPE "B"

Impact Velocity	Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Target Weight Loss (mg)	Erosion* $\varepsilon . 10^6$
42 m/sec	200	30	0.9	4.5
		45	-0.7	- 3.5
		60	-2.1	-10.5
		75	-1.9	- 9.5
		90	-2.8	-14.0
	400	30	2.3	5.7
		45	-0.4	- 1.0
		60	-6.2	-15.5
		75	-3.6	- 9.0
		90	-3.2	- 8.0
	600	30	2.5	4.2
		45	1.0	1.7
		60	-2.8	- 4.7
		75	-4.6	- 7.7
		90	-4.9	- 8.2

TABLE A.4

WEIGHT LOSS DATA FOR POLYURETHANE COATING TYPE "C"

Impact Velocity	Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Target Weight Loss (mg)	Erosion* $\epsilon.10^6$
		30	1.6	8.0
		45	-2.1	10.5
	200	60	-3.1	-15.5
		75	-3.7	-18.5
		90	-4.2	-21.0
		30	1.4	3.5
		45	0.0	0.0
42 m/sec	400	60	-3.0	- 7.5
		75	-4.7	-11.7
		90	-4.8	-12.0
		30	2.0	3.3
		45	0.6	1.0
	600	60	-3.3	- 5.5
		75	-5.2	- 8.7
		90	-5.6	- 9.3

TABLE A.5

WEIGHT LOSS DATA FOR POLYURETHANE COATING TYPE "AB"

Impact Velocity	Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Target Weight Loss (mg)	Erosion* $\varepsilon.10^6$
42 m/sec	200	30	0.9	4.5
		45	-0.5	- 2.5
		60	-1.8	- 9.0
		75	-2.2	-11.0
		90	-2.8	-14.0
	400	30	1.2	3.0
		45	-0.8	- 2.0
		60	-2.2	- 5.5
		75	-3.0	- 7.5
		90	-3.1	- 7.7
	600	30	3.2	5.3
		45	0.7	1.2
		60	-2.7	- 4.5
		75	-3.0	- 5.0
		90	-3.3	- 5.5

TABLE A.6

WEIGHT LOSS DATA FOR POLYURETHANE COATING TYPE "AC"

Impact Velocity	Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Target Weight Loss (mg)	Erosion* $\epsilon.10^6$
42 m/sec	200	30	1.8	9.0
		45	0.0	0.0
		60	-2.0	-10.0
		75	-1.7	- 8.5
		90	-2.6	-13.0
	400	30	0.5	1.2
		45	1.2	3.0
		60	-1.9	- 4.7
		75	-2.8	- 7.0
		90	-3.6	- 9.0
	600	30	4.3	7.2
		45	0.2	0.3
		60	-2.3	- 3.8
		75	-3.5	- 5.8
		90	-3.9	- 6.5

TABLE A.7
WEIGHT LOSS DATA FOR POLYURETHANE TEREPHTHALATE
REINFORCED WITH T-300 CARBON FIBERS
IMPACT VELOCITY -- 42 M/SEC

Impact Velocity	Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Target Weight Loss (mg)	Erosion* $\varepsilon.10^6$
42 m/sec	200	30	37.9	190
		45	109.8	549
		60	157.9	790
		75	204.2	1021
		90	156.6	783
	400	30	75.4	188
		60	277.6	694
		90	434.8	1087
	600	30	111.4	186
		60	367.1	612
		90	665.0	1108

TABLE A.8
WEIGHT LOSS DATA FOR POLYURETHANE TEREPHTHALATE
REINFORCED WITH T-300 CARBON FIBERS
IMPACT VELOCITY -- 74.5 M/SEC

Impact Velocity	Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Target Weight Loss (mg)	Erosion* $\cdot 10^6$
74.5 m/sec	200	30	162.0	810
		45	629.6	3148
		60	915.2	4576
		75	964.3	4821
		90	1071.1	5355
	400	30	585.6	1464
		60	1578.7	3947
		90	2075.8	5190

TABLE A.9

WEIGHT LOSS DATA FOR POLYURETHANE TEREPHTHALATE REINFORCED WITH E GLASS EPOXY FIBERS

Impact Velocity	Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Target Weight Loss (mg)	Erosion* $\varepsilon.10^6$
42 m/sec	200	30	166.1	830
		60	567.4	2837
		90	475.1	2375
	600	30	264.5	441
		60	1383.8	2306
		90	1804.2	3007

APPENDIX B

SURFACE ROUGHNESS DATA

TABLE B.1

SURFACE ROUGHNESS DATA FOR POLYURETHANE
COATING TYPE "A"
IMPACT VELOCITY 42 m/sec

Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Roughness C.L.A. (microns)					Average
Before Erosion		0.43	0.50	0.23	0.36	0.33	0.10 ± 0.37
200	30	0.70	0.63	0.76	0.62	0.55	0.08 ± 0.65
	45	0.80	0.62	0.71	0.67	0.68	0.07 ± 0.70
	60	0.55	0.60	0.62	0.53	0.57	0.04 ± 0.57
	75	0.60	0.47	0.54	0.53	0.55	0.05 ± 0.54
	90	0.51	0.55	0.70	0.52	0.43	0.10 ± 0.54
400	30	0.96	1.00	0.98	1.12	1.30	0.15 ± 1.07
	45	0.80	0.75	0.93	0.68	0.73	0.10 ± 0.78
	60	0.69	0.60	0.64	0.58	0.70	0.05 ± 0.64
	75	0.65	0.51	0.74	0.53	0.63	0.09 ± 0.61
	90	0.38	0.44	0.40	0.42	0.53	0.06 ± 0.43
600	30	1.05	1.10	0.80	1.15	1.00	0.13 ± 1.02
	45	0.90	0.65	0.96	0.68	0.82	0.13 ± 0.80
	60	0.60	0.67	0.55	0.46	0.68	0.09 ± 0.59
	75	0.68	0.61	0.75	0.66	0.40	0.13 ± 0.62
	90	0.61	0.44	0.53	0.44	0.47	0.07 ± 0.50

TABLE B.2

SURFACE ROUGHNESS DATA FOR
POLYURETHANE COATING TYPE "A"
IMPACT VELOCITY -- 74.5 M/SEC

Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Roughness C.L.A. (microns)					Average
Before Erosion		0.43	0.50	0.23	0.36	0.33	0.10± 0.37
200	30	0.70	0.47	0.53	0.58	0.60	0.09± 0.58
	45	1.32	1.25	1.15	0.77	1.10	0.21± 1.12
	60	0.42	0.50	0.60	0.53	0.60	0.08± 0.53
	75	0.57	0.50	0.52	0.92	0.58	0.06± 0.52
	90	0.50	0.39	0.44	0.35	0.40	0.06± 0.42
400	30	1.70	1.60	1.70	1.80	2.25	0.26± 1.81
	45	2.20	2.35	1.75	1.65	1.60	0.34± 1.91
	60	1.00	1.40	0.65	1.00	0.55	0.39± 0.92
	75	0.44	0.52	0.73	0.40	0.45	0.13± 0.51
	90	0.36	0.40	0.44	0.50	0.42	0.05± 0.42
600	30	2.20	2.20	2.10	1.90	2.35	0.17± 2.15
	45	2.45	2.50	2.60	2.50	2.15	0.12± 2.56
	60	1.00	1.15	1.00	1.55	1.27	0.23± 1.19
	75	0.36	0.74	0.84	0.52	0.63	0.19± 0.62
	90	0.45	0.48	0.62	0.40	0.46	0.08± 0.48

TABLE B.3

SURFACE ROUGHNESS DATA FOR
POLYURETHANE COATING TYPE "B"
IMPACT VELOCITY -- 42 M/SEC

Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Roughness C.L.A. (microns)					Average
Before Erosion		0.20	0.26	0.20	0.31	0.23	0.05 ± 0.24
200	30	0.49	0.57	0.54	0.53	0.53	0.03 ± 0.53
	45	0.62	0.70	0.65	0.56	0.87	0.12 ± 0.68
	60	0.66	0.50	0.62	0.51	0.56	0.07 ± 0.57
	75	0.39	0.38	0.47	0.45	0.36	0.05 ± 0.41
	90	0.52	0.42	0.50	0.49	0.44	0.04 ± 0.47
400	30	0.96	0.96	1.10	0.95	0.92	0.07 ± 0.98
	45	0.73	1.10	0.95	1.25	1.00	0.19 ± 1.01
	60	0.65	0.72	0.75	0.59	0.62	0.07 ± 0.67
	75	0.56	0.57	0.48	0.53	0.50	0.04 ± 0.53
	90	0.44	0.46	0.56	0.40	0.40	0.07 ± 0.45
600	30	1.10	1.20	1.30	1.26	1.15	0.08 ± 1.20
	45	1.20	1.35	1.50	1.17	1.40	0.14 ± 1.32
	60	0.70	0.88	0.69	0.80	0.78	0.08 ± 0.77
	75	0.62	0.55	0.62	0.60	0.63	0.03 ± 0.60
	90	0.64	0.54	0.54	0.48	0.55	0.06 ± 0.55

TABLE B.4

SURFACE ROUGHNESS DATA FOR
POLYURETHANE COATING TYPE "C"
IMPACT VELOCITY -- 42 M/SEC

Amount of Sand Impacted (gr)	Impingement Angle (degrees)	Roughness C.L.A. (microns)					Average
Before Erosion		0.20	0.28	0.24	0.20	0.21	0.03 ± 0.23
200	30	0.64	0.73	0.76	0.48	0.76	0.12 ± 0.67
	45	0.60	0.80	0.90	0.84	0.75	0.11 ± 0.78
	60	0.50	0.66	0.61	0.50	0.61	0.07 ± 0.58
	75	0.45	0.47	0.58	0.50	0.47	0.05 ± 0.49
	90	0.43	0.46	0.47	0.49	0.45	0.02 ± 0.46
400	30	0.85	0.98	1.05	1.00	0.78	0.11 ± 0.93
	45	1.15	1.10	1.50	1.25	1.35	0.16 ± 1.27
	60	0.70	0.93	0.70	1.00	1.05	0.17 ± 0.88
	75	0.60	0.53	0.48	0.48	0.66	0.08 ± 0.55
	90	0.46	0.55	0.51	0.54	0.52	0.03 ± 0.52
600	30	1.10	1.10	1.05	1.00	1.18	0.07 ± 1.09
	45	1.32	1.38	1.60	1.30	1.55	0.14 ± 1.93
	60	0.77	0.98	1.25	1.15	1.25	0.20 ± 1.08
	75	0.60	0.70	0.63	0.60	0.80	0.09 ± 0.67
	90	0.50	0.55	0.55	0.54	0.58	0.03 ± 0.54

*USGPO: 1983-659-062-963

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